

Hydrodynamic optimisation and thermodynamic scaling fidelity of single and dual-chamber OWC wave energy converters in regular waves

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ABSTRACT

This study experimentally investigates the hydrodynamic optimisation and scaling fidelity of five oscillating water column (OWC) configurations: three single-chamber geometries (Conventional, U-OWC, L-OWC) and two novel dual-chamber hybrids (DCOWC-1 and DCOWC-2). Conducting 792 tests at 1:30 scale under regular waves, the campaign quantified the influence of air compressibility by contrasting correct thermodynamic scaling (using external expansion chambers) against the traditional incompressible method across pneumatic damping levels of $Or = 0.4\text{--}1.6\%$. The compressible configuration creates a softer air spring effect, increasing wave discharge rates while decreasing pneumatic pressure; consequently, incompressible methods typically underestimated airflow and overestimated pressure damping. Under correctly scaled conditions, the U-OWC demonstrated superior capability and broad bandwidth, achieving a peak capture width ratio (CWR) of 0.79 at a dimensionless frequency $B/L = 0.08$, surpassing the Conventional ($CWR = 0.48$) and L-OWC ($CWR = 0.46$) geometries. The U-OWC proved highly sensitive to thermodynamic modelling: neglecting compressibility caused a 43% underestimation of peak efficiency under high damping, indicating incompressible experiments may misrepresent prototype-scale performance. Conversely, the L-OWC remained robust (5.4% deviation), while the Conventional OWC showed moderate sensitivity (12.5% underestimation and a resonance shift). For total energy extraction, the dual-chamber hybrids extended operational bandwidth via a double-peak mechanism: the superior DCOWC-2 reached a peak CWR of 0.85, nearly 31% higher than DCOWC-1, and maintained $CWR > 0.50$ across $B/L = 0.03\text{--}0.09$. This validates a mixed-damping strategy applying high pneumatic damping to the front U-OWC and lower pneumatic damping to the rear L-OWC to independently optimise each chamber.

1. Introduction

Ocean wave energy is globally recognised as a dense, reliable, and predictable source within the marine renewable energy portfolio (Falcão, 2010). Among the various wave energy converters (WECs), the fixed oscillating water column (OWC) device is distinguished by its structural simplicity and established technology readiness, often favouring its integration into coastal infrastructure like breakwaters (Falcão and Henriques, 2016; Opoku et al., 2023). OWCs operate by confining a column of water in a submerged chamber, where wave action induces oscillation of the internal free surface. This oscillation dynamically compresses and expands the air volume in the chamber, generating a reciprocating air flow that drives an air turbine, which

constitutes the power take-off (PTO) system (Falcão and Henriques, 2016). Achieving commercial viability for OWC systems requires systematic maximisation of the primary conversion efficiency, typically measured by the capture width ratio (CWR). This optimisation involves two interdependent physical processes. First, hydrodynamic geometry optimisation focuses on adjusting the structural features of an OWC, such as the front-wall draught and the duct geometry, to tune its natural resonant period (T_r) aiming to match the dominant wave periods at the site. This alignment enhances the chamber's oscillation response and maximises the water-column response amplitude operator (RAO_c) (López et al., 2021). Second, pneumatic damping optimisation seeks to match the damping provided by the PTO system to the inherent hydrodynamic radiation damping of the OWC, which is essential for

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maximising energy capture. To accurately characterise these performance mechanisms, controlled physical model tests in flumes or basins are critical for establishing the fundamental, mainly frequency-dependent, performance envelope, finding the resonance condition, and generating the necessary physical model data for validating numerical models used in frequency-domain analysis. The initial and most extensively studied configuration is the Conventional OWC, also known as the traditional OWC. This baseline geometry features a simple vertical seaward wall and a horizontal submerged opening, defining a standard rectangular chamber. Conventional OWCs have reached full-scale deployment through projects such as the Pico, LIMPET and Mutriku plants, demonstrating the technological maturity of the basic concept (Heath et al., 2001; Torre-Enciso et al., 2009; Falcão et al., 2020). The resonant characteristics of the Conventional OWC are limited primarily by the chamber depth and front wall draught (López et al., 2021). However, the simple geometry offers limited tuneability for aligning the natural frequency with optimal wave periods, and it is susceptible to structural issues, such as air being drawn from the exposed side during severe wave troughs (Boccotti, 2007).

As limitations in tuneability and robustness remain key challenges for the Conventional OWC, several advanced geometric concepts have been proposed to improve resonance performance and energy absorption capabilities (Ashlin et al., 2016). One widely investigated configuration is the U-shaped OWC (U-OWC), also known as the resonant wave energy converter (REWEC), which features an additional vertical duct that significantly increases the effective length of the OWC (Boccotti, 2007). This geometric feature is critical as it allows for a greater increase in the structure's eigenperiod, enabling better resonance matching with longer period swells typical of many target sites (Malara and Arena, 2013). The hydrodynamic superiority of the U-OWC configuration over conventional single-chamber architectures is driven by its broadband frequency response, a characteristic explicitly demonstrated in monochromatic (regular) wave campaigns. Physical flume testing under regular waves reveals that while Conventional OWCs exhibit a sharp, narrow resonant peak, the U-OWC's extended vertical duct alters the internal fluid inertia, significantly broadening the effective Capture Width Ratio (CWR) curve across a wider range of incident wave periods (Vyzikas et al., 2017).

The expanded resonant bandwidth observed under regular waves suggests improved energy-extraction potential under realistic stochastic sea states. Because the U-OWC avoids the rapid off-resonance efficiency collapse characteristic of Conventional OWCs, it is highly effective at absorbing energy from broad-spectrum irregular waves. Analytical evaluations of irregular wind-wave spectra confirm this operational advantage; under specific stochastic conditions, the U-OWC can sustain an energy absorption coefficient of 0.91, whereas the narrow-band Conventional OWC collapses to an average absorption of merely 0.16 (Boccotti, 2007). Furthermore, the U-OWC geometry provides inherent structural survivability; the submerged seaward duct maintains sufficient internal hydrostatic elevation to resist inlet broaching (air-sucking) during extreme wave troughs, a failure mode to which Conventional open-bottom OWCs remain highly vulnerable.

Another promising configuration is the L-shaped OWC (L-OWC), which incorporates a horizontal entrance duct that allows geometric adjustments to tune the effective OWC length (Samak, 2021). This arrangement is also characteristic of several floating devices, such as the backward-bent duct buoy (Masuda et al., 1999). Experimental studies have shown that the L-shaped duct OWC behaves like a single-degree-of-freedom oscillatory system, with its performance, particularly its primary efficiency, increasing near the natural resonant frequency when the immersion depth is optimised (Rezanejad et al., 2019). Numerical investigations further indicate that certain L-OWC variants can achieve CWRs of up to 0.72 (López et al., 2021).

Despite these advances, single-chamber OWCs generally remain narrow-band devices, with energy capture concentrated around a principal resonant region and declining as the incident-wave frequency

moves away from the optimum range. This limitation has motivated the development of dual- and multi-chamber arrangements designed to broaden the effective energy-capture bandwidth (Fu et al., 2023, 2025; Yang et al., 2025). To achieve this, multi-chamber OWCs combine multiple water columns and pneumatic chambers whose interacting responses can improve energy extraction over a wider range of incident-wave frequencies (Ning et al., 2019; Rezanejad et al., 2015; Mia et al., 2022). Dual-chamber configurations, in particular, have demonstrated broader effective frequency ranges and improved performance relative to comparable single-chamber devices under the investigated conditions (Mandev et al., 2024; Ning et al., 2024). Experimental comparisons conducted with the same total device width have shown that multi-chamber arrangements can improve hydrodynamic energy extraction relative to a traditional single-chamber configuration, although the overall efficiency may decline when the number of chambers becomes excessive (Ning et al., 2024). CFD studies of offshore-stationary dual-chamber OWCs report maximum CWR improvements of approximately 140% over intermediate-to-long wave periods when three-dimensional effects are considered (Elhanafi et al., 2018). Building on this evidence, the present study investigates whether pairing geometrically distinct OWC chambers can provide complementary frequency responses within a single dual-chamber system.

Alongside such geometric hybridisation, recent research has increasingly moved from overall structural optimisation towards chamber-level pneumatic coordination. Multi-chamber multi-turbine arrangements divide a large OWC chamber into independently operated chamber-turbine modules, reducing the performance losses that may arise when out-of-phase chamber responses are connected to a shared turbine (Mia et al., 2022; Cong et al., 2024). Segmenting the chamber can also convert sloshing-mode free-surface motion into separate piston-mode responses, thereby improving peak efficiency and effective operating bandwidth (Cong et al., 2024). Analytical and semi-analytical studies of cylindrical multi-chamber OWCs further demonstrate that chamber number, chamber width, outer-shell draught and angular chamber extent influence the hydrodynamic efficiency and operating bandwidth of the device (Qian et al., 2024; Spanò et al., 2025). However, the hydrodynamic interaction between chambers having fundamentally different internal water-column paths and geometries within the same dual-chamber unit remains comparatively less explored. Another important design consideration is the relationship among wave reflection, pneumatic energy extraction and viscous dissipation. He et al. (2024) showed that the wave frequency producing minimum reflection does not necessarily coincide with that producing maximum energy extraction because part of the incident energy may be lost through vortex-related dissipation. Reflection, extraction and dissipation should therefore be considered jointly during hydrodynamic optimisation. Structural wave loads require separate consideration, particularly around the front lip, rear wall and structural connections of multi-chamber devices (Fu et al., 2024).

A further determinant of OWC performance is the matching of PTO damping to the chamber hydrodynamics. In reduced-scale experiments, turbine resistance is commonly represented using vents or orifice openings that impose a nonlinear pressure-flow relationship (Crema et al., 2024; Gadelho et al., 2024). Crema et al. (2024) demonstrated that the best-performing condition depends jointly on pneumatic damping, chamber length and front-wall draught. Similarly, Gadelho et al. (2024) showed that the performance of an onshore stepped-bottom dual-chamber OWC is highly sensitive to PTO damping, with tested orifice ratios ranging from 0.3% to 0.8% and primary efficiency reaching approximately 40% across a broad range of wave periods. These findings show that the optimum operating condition cannot be represented by a universal damping value but must be identified for each chamber geometry and operating regime.

While recent studies have established the benefits of chamber segmentation and chamber-level PTO coordination, many existing multi-

chamber concepts still employ repeated chamber modules, conventional serial partitions or geometrically similar chamber arrangements (Mia et al., 2022; Fu et al., 2023; Qian et al., 2024). Cong et al. (2024) extended this line of research by showing that identical cross-sectional shapes across chamber modules may not always be optimal for maximising wave-energy capture. Nevertheless, comparatively little attention has been given to integrating fundamentally different, established OWC geometries, such as Conventional, U-shaped and L-shaped OWCs, within a single caisson-type system. The coupling between these dissimilar water-column paths and their potential to target complementary frequency ranges therefore remains insufficiently explored.

A separate but equally important methodological challenge concerns the accurate scaling of air compressibility in physical OWC models. Model-scale OWC testing must simultaneously satisfy Froude similitude for the hydrodynamics and dynamic similarity for the air-phase thermodynamics (Falcão and Henriques, 2014; Sheng and Lewis, 2016). Although Froude scaling is appropriate for gravitational wave interaction, correct thermodynamic similitude requires the chamber air volume to scale with the square of the geometric scale ratio (ε^2), rather than with the cubic relationship (ε^3), associated with geometric volume scaling (Falcão and Henriques, 2014; Sheng and Lewis, 2016). An external air reservoir, or expansion chamber, must therefore be connected to the model air chamber to reproduce the required air-volume distortion and the associated spring-like effect of the compressed air (Falcão and Henriques, 2014). When this requirement is neglected, the resulting performance errors depend strongly on the wave frequency and PTO damping. For wave periods shorter than the system resonance, $T < T_r$, an inadequately scaled air volume can lead to underestimation of the internal water-column motion and CWR by as much as 30% (López et al., 2020). At the primary resonance period, neglecting the spring-like effect of air compressibility can lead to an overprediction of the maximum OWC efficiency by approximately 12% under the optimum PTO-damping condition (Elhanafi et al., 2017). More generally, the magnitude and sign of the resulting error depend on the incident-wave conditions and turbine-induced damping, meaning that neglecting air compressibility may produce either under- or overpredictions of pneumatic power and CWR (López et al., 2020). Comparable CFD scaling analyses have reported chamber-pressure overpredictions of up to approximately 15%, while the corresponding CWR errors remained below 10% under the investigated conditions (Simonetti et al., 2018).

Scaling fidelity therefore remains a critical consideration in OWC physical modelling because conventional geometric Froude scaling does not correctly reproduce the spring-like air-compressibility effect at prototype scale. Experimental and numerical investigations of floating coaxial-duct OWC configurations further demonstrate that air-volume scaling can significantly alter the device hydrodynamics and power performance, with compressibility producing positive, negative, or approximately neutral effects depending on the operating frequency and PTO damping (Portillo et al., 2023). Furthermore, theoretical similarity analyses indicate that scale-dependent thermodynamic effects may be represented through changes in the effective polytropic behaviour of the chamber air. These analyses suggest that non-equilibrium thermodynamic states, which may be less evident in reduced-scale models, can become increasingly relevant as the system approaches prototype scale, with corresponding consequences for predicted OWC performance (Molina-Salas et al., 2023).

First, to the authors' knowledge, no previous study has reported a hybrid dual-chamber system that integrates fundamentally different OWC geometries, such as Conventional, U-shaped and L-shaped water-column paths, within a single caisson-type structure. Second, although these single-chamber configurations are individually well documented, limited work has compared them within a common experimental and thermodynamic-scaling framework, restricting the availability of a consistent benchmark dataset. Third, the geometry-dependent consequences of correct air-volume scaling have not been systematically

resolved across both established single-chamber and hybrid dual-chamber configurations. These gaps motivate the unified experimental investigation presented in this study.

Accordingly, this study provides a systematic side-by-side evaluation of multiple OWC configurations and assesses the thermodynamic scaling required for reliable prototype-scale representation. These contributions are pursued through two integrated objectives. The first objective is to compare the pneumatic power extraction of five OWC systems across a range of orifice ratios. The tested configurations comprise three established single-chamber devices, namely the Conventional OWC, U-OWC and L-OWC, and two novel dual-chamber concepts, DCOWC-1 and DCOWC-2 (see Section 3.2). The single-chamber configurations are tested within a unified experimental framework to provide a consistent benchmark for evaluating the proposed hybrid systems. The dual-chamber concepts combine the distinct geometric and hydrodynamic characteristics of the Conventional, U-shaped and L-shaped OWCs within a single caisson. Their design is based on the premise that chambers with different water-column paths and resonance characteristics can target complementary portions of the incident-wave frequency range, thereby broadening the effective operating bandwidth and increasing energy capture per unit width without enlarging the breakwater footprint. This concept is also compatible with the practical integration of OWCs into caisson-type breakwaters, where landward cells that would otherwise remain empty or sand-filled may be repurposed as functional OWC chambers, provided that global stability requirements, including overturning, sliding and bearing capacity, are satisfied. The second objective is to quantify the influence of air-compressibility scaling across the tested geometries. Comparative experiments are conducted with and without external air-expansion chambers under identical wave and structural conditions. The expansion-chamber configuration reproduces the required air-elasticity scaling, whereas the blanked configuration represents the conventional incompressible approximation used in reduced-scale testing. Comparing these configurations enables the performance deviation caused by neglecting air compressibility to be quantified and provides an experimental assessment of the thermodynamic-scaling framework required for reliable prototype-scale prediction.

Within this controlled framework, regular-wave testing is used to isolate the governing hydrodynamic and thermodynamic mechanisms of each configuration, including resonance behaviour, pneumatic-damping sensitivity, chamber-to-chamber interaction and air-compressibility effects. The resulting responses therefore establish a frequency-dependent benchmark for evaluating the behaviour of the same systems under more realistic sea conditions. Since natural seas contain broadband spectral energy and wave-group variability, the peak responses and operating bandwidths reported here should not be interpreted as direct estimates of annual energy capture or structural survivability. Instead, they establish a controlled physical basis for the subsequent evaluation of the same configurations under unimodal and bimodal irregular-wave spectra.

This study is structured as follows: After this introduction, the theoretical framework and utilised hydrodynamic relations are summarised in Section 2. The experimental setup and methods are presented in Section 3, detailing the modular model design, instrumentation, and the specific thermodynamic scaling procedures employed. Section 4 presents the experimental results and discussion, offering a systematic comparative analysis of the hydrodynamic response, pneumatic behaviour, and energy capture efficiency for both single and dual-chamber configurations. This section also quantifies the critical effects of air compressibility and evaluates the wave reflection characteristics. Finally, Section 5 concludes the paper with a summary of the principal findings and outlines the roadmap for future work in stochastic environments.

2. Theoretical background of hydrodynamic relations

This section outlines the fundamental theoretical framework and hydrodynamic definitions used to evaluate the performance of the OWC configurations. The analysis focuses on quantifying the primary energy conversion efficiency, characterising the resonant response of the OWC and air chamber, and assessing the wave-structure interaction phenomena, including wave reflection and run-up, under regular wave conditions. The system performance is characterised through four key hydrodynamic parameters: the internal water surface elevation (RAO_c), chamber air pressure fluctuation (RAO_p), capture width ratio (CWR), and wave reflection coefficient (C_R). The OWC system's operational theory is often predicated on treating the internal water column as a vertically oscillating rigid piston (López et al., 2021). For narrow chambers, the natural resonance frequency (ω) can be hydrostatically estimated as $\omega = \sqrt{g/a}$, where (a) is the length of immersion and (g) is gravitational acceleration (López et al., 2021). The resonance behaviour governs the dynamic motion of the internal water column and strongly affects the efficiency of energy transfer between the incident waves and the enclosed air chamber. When the OWC operates close to its natural frequency, the resulting air pressure variations become substantial, driving pneumatic energy conversion through the PTO mechanism (Falcão, 2010; Evans and Porter, 1995; Henriques et al., 2016).

Performance is initially evaluated through response amplitude operators (RAO), which quantify motion amplification driven by resonance. The hydrodynamic response of the internal free surface is presented in Equation (1):

$$RAO_c = \frac{H_c}{H_i} \quad \text{Eq. 1}$$

and the pneumatic amplification is shown in Equation (2):

$$RAO_p = \frac{\Delta p_H}{\rho_w g H_i} \quad \text{Eq. 2}$$

where H_c and Δp_H represent the internal free-surface height and the pneumatic pressure fluctuation range inside the chamber, respectively, while H_i is the incident wave height and ρ_w is the water density. Peak RAO values typically occur near resonance, aligning with optimal energy capture. To quantify the energy available to the system, the incident wave power per unit crest length (P_i) is defined in Equation (3):

$$P_i = \frac{1}{8} \rho_w g H_i^2 C_g \quad \text{Eq. 3}$$

where (C_g) is the group velocity. The measurable performance of an OWC is fundamentally defined by its ability to convert wave energy into useful pneumatic power. The pneumatic power (P_{abs}) represents the mean power absorbed by the PTO system and is evaluated by integrating the instantaneous air pressure $p(t)$ across the orifice and the instantaneous volumetric airflow rate $Q(t)$ over the duration of one wave cycle (T) (Falcão and Henriques, 2016; López et al., 2020), as shown in Equation (4):

$$P_{abs} = \frac{1}{T} \int_0^T p(t) Q(t) dt \quad \text{Eq. 4}$$

To provide a normalised measure of efficiency, the CWR relates the extracted pneumatic power (P_{abs}) to the incident wave power (P_i) across the flume width (w_c) as defined in Equation (5):

$$CWR = \frac{P_{abs}}{w_c P_i} \quad \text{Eq. 5}$$

For the dual-chamber devices (detailed in Section 3.2), the total energy harvesting capability is evaluated by summing the capture width ratios of the front and rear individual compartments, following the

approach of Gadelho et al. (2024). It is important to note that the incident wave power P_i used in this summation is a single, shared value derived from the far-field incident wave height; it is not duplicated for each chamber, as both compartments are excited by the same incoming wave energy package, as given in Equation (6):

$$CWR_{Total} = CWR_{Front} + CWR_{Rear} \quad \text{Eq. 6}$$

While CWR and the RAOs describe how effectively the chamber converts incident waves into pneumatic power, not all incoming wave energy is extracted; a portion is reflected at the OWC aperture, reducing the energy available for conversion. The reflection coefficient quantifies this loss, as defined in Equation (7):

$$C_R = \frac{H_r}{H_i} \quad \text{Eq. 7}$$

where H_r is the reflected-wave height and H_i is the incident wave height. The incident and reflected wave components were separated from the offshore wave gauge records using the least-squares method proposed by Mansard and Funke (1980).

Finally, to explicitly quantify the error introduced by the traditional Froude-scaling approach, the percentage deviation ξ_{error} is calculated using the compressible configuration as the true reference value, as shown in Equation (8):

$$\xi_{error} = \frac{CWR_{comp} - CWR_{incomp}}{CWR_{comp}} \times 100 \quad \text{Eq. 8}$$

where CWR_{comp} represents the efficiency of the compressible configuration and CWR_{incomp} denotes the result from the incompressible setup.

3. Experimental setup and procedures

3.1. Wave flume and scaling

The experimental campaign was carried out in the COAST Laboratory at the University of Plymouth, using a wave flume that measures 20.0 m in length, 0.6 m in width, and 0.8 m in height. The OWC models were designed and constructed according to Froude similarity with a geometric length-scale ratio of 1:30. Although no direct prototype exists for the present study, the dimensions of the U-OWC incorporated into the front segment of the dual chamber OWC tested in the present study (DCOWC-2, see Section 3.2) are based on the Port of Salerno breakwater geometry described by Romolo et al. (2025), with modifications in experimental conditions including the water depth in front of the structure. Overall, the dual-chamber arrangements represent novel configurations developed specifically for this research.

Wave generation was achieved using a piston-type wave paddle equipped with an active wave absorption control system based on a force-feedback mechanism. This system minimises secondary reflections and suppresses spurious re-reflections from the paddle, maintaining a stable incident wave field throughout testing. A side view of the flume is presented in Fig. 1, including the wave paddle, model location, and instrumentation layout. As shown in this Figure, still-water depth was maintained at 0.50 m for all tests.

3.2. Modular OWC models and their geometry

A modular dual-chamber OWC model was purpose-built to allow for the systematic modification of the geometry. By changing the inlet configuration and blocking or opening specific ducts, the same base structure could reproduce five target geometrical arrangements: the Conventional OWC, the U-OWC, the L-OWC, and the two dual-chamber hybrid forms (DCOWC-1 and DCOWC-2). This modular approach ensured identical structural, material, and instrumentation characteristics across all configurations, eliminating fabrication-induced variability and enabling a direct performance comparison. Fig. 2 presents sectional

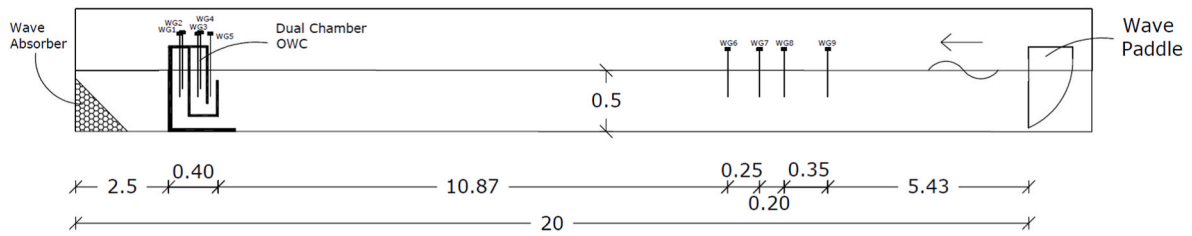


Fig. 1. The side view showing the full wave flume, wave paddle, wave absorber, OWC location (dimensions are in metres).

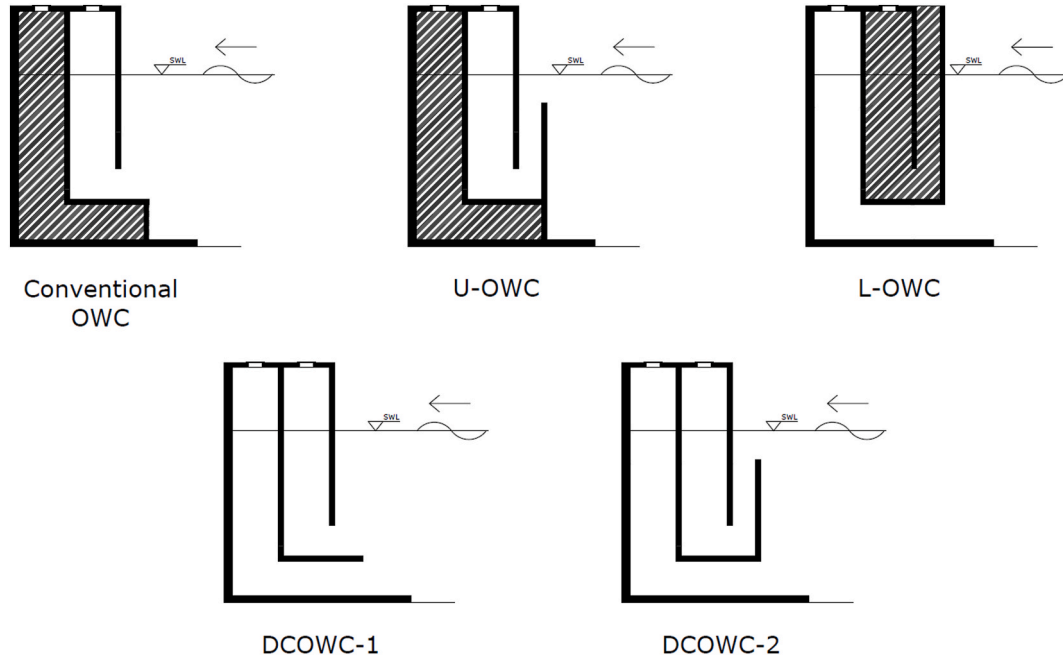


Fig. 2. The schematic showing the cross-sections of the five OWC types.

views illustrating the geometric variations among these five OWC types.

The model was fabricated from transparent Perspex (acrylic) to allow visual inspection of internal water motion and air–water interaction. All joints were sealed with marine-grade silicone and mechanically reinforced to ensure airtightness under cyclic loading. Each configuration was leak-tested prior to experimentation, confirming negligible air loss and stable chamber integrity throughout testing. Fig. 3 provides photos of the assembled modular OWC model installed in the wave flume, illustrating its construction and instrumentation layout.

Each model extended across the full flume width (0.6 m) and was subdivided into two orthogonally oriented compartments (perpendicular to the incoming wave direction) to suppress sloshing and cross-wave resonance modes. To define the dimensions of the OWC structures, Fig. 4 provides a detailed cross-sectional view of the double-chamber modular structure and labels 15 key geometric parameters. These dimensions define the chamber hydrodynamics and are categorised by the overall dimensions, chamber components, and structural thickness. The primary dimensions include the still-water depth (h), the total structural width (C), overall base length (f), and the upstream base extension (g). Key chamber component dimensions are the front and back chamber widths (B), front chamber bottom opening depth (a), vertical duct width (s), air chamber height overall (l), horizontal base length of the internal chamber (k), and back chamber bottom opening depth (e). Finally, the structural dimensions detailing the thickness of the model elements are defined by the roof thickness ($tk1$), the base thickness ($tk2$), and the upstream wall thickness ($tk3$). It should be noted that the remaining structural elements were also constructed using the

thickness specified by ($tk1$). The orifice ratio (Or) is also a critical operational parameter, which is defined as the ratio of orifice opening area to chamber plan area. These 15 primary and secondary geometric parameters are summarised in Table 1.

3.3. Instrumentation and measurements

The experimental setup integrated hydrodynamic, pneumatic, and thermodynamic instrumentation operating simultaneously to ensure coherent temporal resolution of all dynamic variables.

3.3.1. Water surface elevation measurements and wave conditions

Free-surface elevations were measured using nine resistive-type wave gauges (WG). Four gauges were positioned in the offshore section (WG6–WG9, see Fig. 1) to monitor the generated waves. Four gauges (WG1–WG4) were positioned within the OWC chambers, two in the front and two in the rear compartments, to measure internal water column displacement. Finally, wave gauge WG5 was mounted directly against the exterior face of the front wall to specifically measure the wave run-up on the structure. To ensure measurement reliability, all resistive wave gauges and internal free-surface probes were calibrated at the beginning of the experimental campaign using three known vertical water-level positions with 5 cm spacing. The resulting calibration coefficients were applied to convert voltage signals into free-surface elevation. The incident wave conditions were calibrated separately in the empty flume before installing the OWC model. For this purpose, reflection analysis was applied to the offshore wave-gauge array to

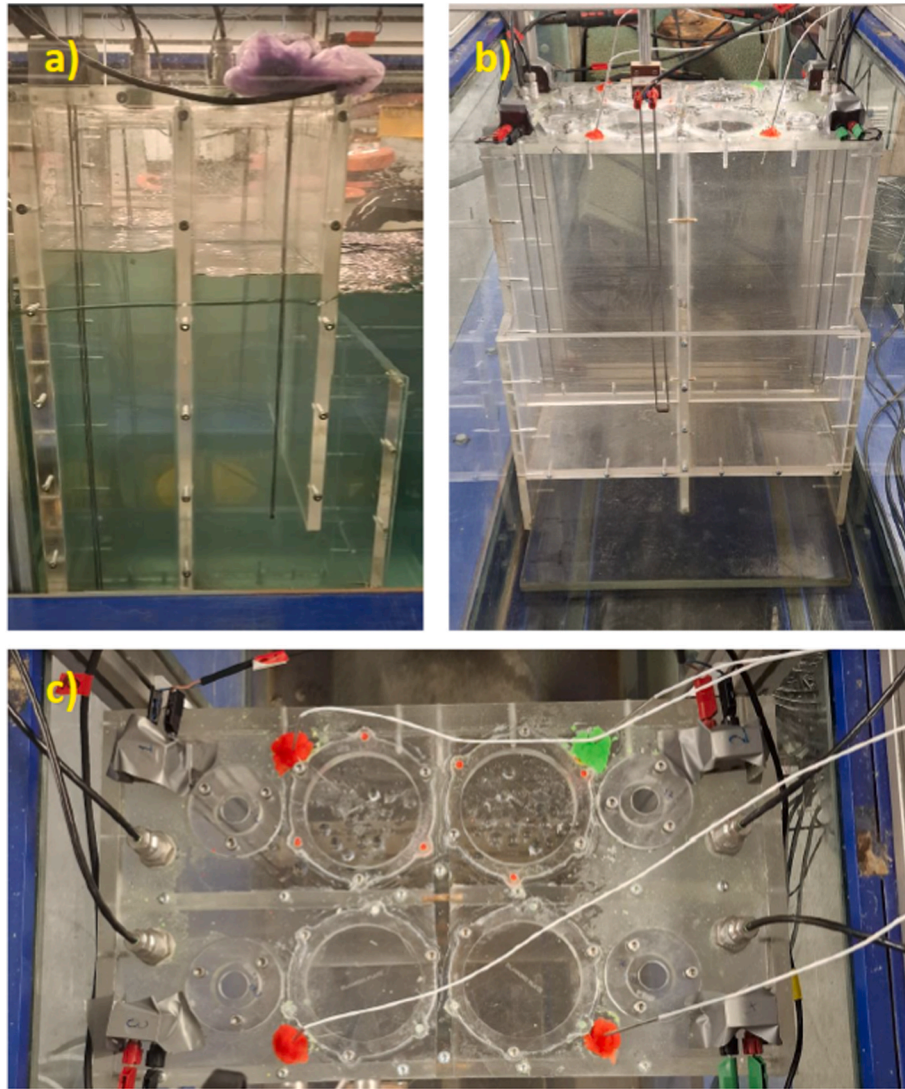


Fig. 3. (a) Side view (here, in the U-OWC configuration) showing the water column and lip submergence; (b) front view illustrating the full segmented chamber depth; (c) top view of the instrumented roof.

separate the incident and reflected components and verify that the target regular-wave height and period were reproduced consistently at the model location. Once validated, the corresponding paddle-control time series were saved and reused for the subsequent OWC tests. To ensure a statistically stable quasi-steady state, 60 regular wave cycles were generated for all individual experiments. To eliminate transient start-up and decay effects, the initial 10 and final 10 waves were excluded, and the data analysis was performed using the mean values of the central 40 stable cycles. Wave Set 1, comprising seventeen tests, maintained a near-constant wave steepness of $s_m = 0.02$, providing a consistent baseline for comparison under linear wave conditions. This set was used primarily for identifying the resonant frequency of each geometry across a range of periods. Wave Set 2 (six tests) systematically varied the wave steepness from 0.012 to 0.05 at a constant prototype wave height of $H_m^{pro} = 1.8$ m, enabling the examination of the effect of wave period on OWC efficiency. A summary of the regular wave conditions used for model testing, characterised by the arithmetic mean wave height (H_m) and mean wave period (T_m) derived from the down zero-crossing analysis of the steady-state window, along with the resulting wave steepness (s_m) and corresponding prototype values, is provided in Table 2.

3.3.2. Pneumatic and thermodynamic measurements

Chamber-air pressure relative to ambient atmospheric pressure was measured using four factory-calibrated KELLER PR-25Y gauge-pressure transmitters (PT), each with a measurement range of 0–0.5 bar and a 0–10 V analogue output. The transmitters recorded the instantaneous chamber-to-ambient pressure difference, Δp , and the manufacturer calibration relation was used to convert the voltage signals into pressure. The PTO system was simulated using interchangeable circular orifice plates mounted at the top of each air duct. These orifices imposed controlled pneumatic damping representative of turbine aerodynamic resistance, consistent with the standard orifice-plate analogue for a quadratic pressure–flow response.

To evaluate the sensitivity of pneumatic power absorption to PTO damping, ten orifice plates corresponding to orifice area ratios (Or) between 0.4% and 3.5% were tested in preliminary trials. Each plate was precision CNC-machined from Perspex and sealed to minimise leakage and ensure consistent flow-contraction characteristics. However, to maintain a manageable number of tests for comparative analysis, a reduced set of five representative orifice ratios (0.4%, 0.6%, 0.8%, 1.2%, and 1.6%) was selected. During preliminary repeatability testing, measurement consistency was verified using the Conventional OWC under the same representative regular-wave condition. For this purpose, each of the five orifice ratios was tested three times under identical incident-

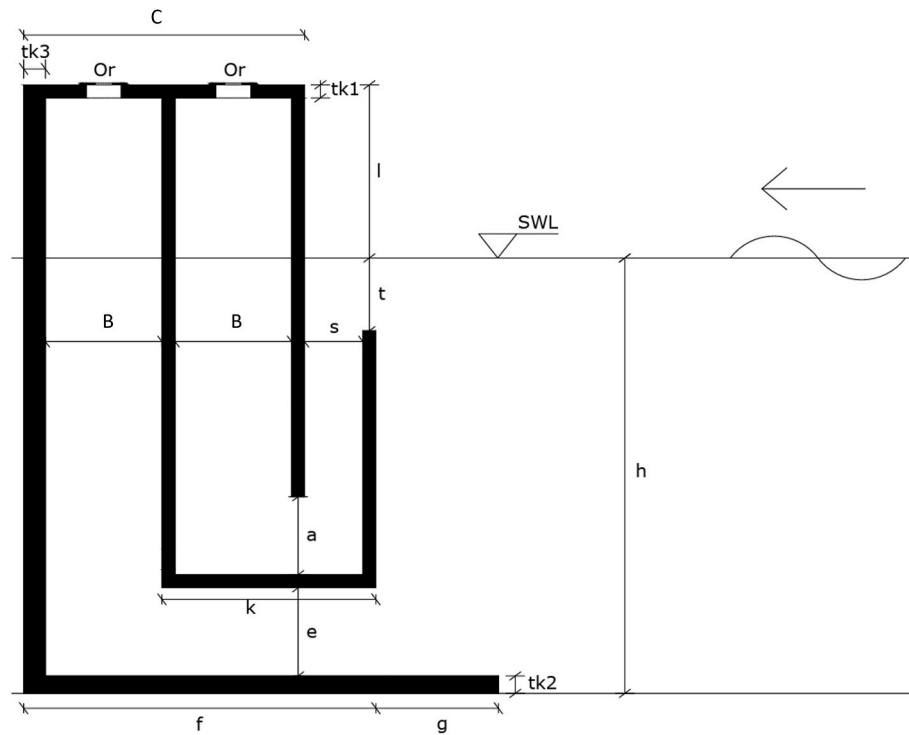


Fig. 4. Detailed cross-sectional view of the modular OWC structure, labelling key geometric parameters.

Table 1

Geometric parameters of the modular OWC model associated with Fig. 4 (dimensions are given in metres).

h	a	B	t	l	k	e	s
0.50	0.09	0.134	0.084	0.20	0.245	0.101	0.067
C	f	g	Or	$tk1$	$tk2$	$tk3$	-
0.324	0.404	0.14	0.4-1.6%	0.015	0.02	0.025	-

Table 2

Summary of regular wave conditions for model testing.

	Model		Prototype		s_m
	H_m (m)	T_m (s)	H_m (m)	T_m (s)	
Set 1	0.028-0.107	0.95-2.55	0.83-3.21	5.2-14	0.02
Set 2	0.06	0.87-2.45	1.77	4.8-13.4	0.012-0.05

wave forcing. The resulting free-surface elevation and chamber-pressure signals showed high consistency, with the coefficient of variation across the triplicate runs remaining below 1.5% for the peak free-surface elevation and below 2.5% for the peak chamber pressure. The air chambers, air ducts and expansion-chamber connections were also checked for leakage, and no air leakage was observed during the experiments. This confirmed that the measured pressure response was produced by the intended pneumatic damping and air-volume configuration rather than by uncontrolled pneumatic losses.

This subset was chosen based on the individual behaviour of each structure, as the maximum efficiency range indicated by the CWR was consistently observed within this interval during preliminary optimisation sweeps; the remaining five orifice sizes were therefore excluded from the present experimental dataset. From these selected plates, the optimal orifice for each OWC configuration was then applied to determine its peak performance range. The full set of orifice plates is listed in Table 3. Fig. 5 provides a top-down view of the OWC roof, showing the locations of the orifice plates and the pneumatic and thermodynamic

Table 3

Orifice plate parameters used in the experimental PTO simulation.

Plate Number	Orifice Ratio (Or) %	Diameter (ϕ) (mm)
1	0.4	13.5
2	0.6	16.5
3	0.8	19.1
4	1.2	23.4
5	1.6	27.0

sensors within the dual-chamber configuration.

All instrumentation was synchronised through a National Instruments data-acquisition system operating at a sampling frequency of 128 Hz. This sampling rate is consistent with the ranges commonly employed in OWC laboratory experiments, where similar frequencies have been used for the acquisition of water-level and internal-pressure signals (Jacob, 2019; Vyzikas et al., 2017). It also satisfies the Nyquist requirement for the highest energy-carrying frequencies in the wave and pneumatic responses, ensuring adequate temporal resolution for the present tests (Jerri, 1977). All signals were low-pass filtered to remove electrical noise prior to time-domain processing.

3.4. Test methodology: compressible and incompressible configurations

Two operational configurations were employed to examine both the hydrodynamic response of the OWC systems and the influence of air compressibility scaling on their pneumatic behaviour. In the compressible configuration, the model was connected to an external rigid air reservoir (expansion chamber) to reproduce the correct air elasticity scaling between model and prototype. To achieve this, the ratio of model-to-prototype air volume was adjusted according to the square of the geometric scale ratio (ϵ^2) rather than the cubic ratio (ϵ^3) dictated by geometry. The exact relationship for the model volume (V_m) relative to the prototype volume (V_p) is given in Equation (9).

$$\frac{V_m}{V_p} = \frac{\kappa_m}{\kappa_p} \epsilon^2 \delta^{-1} \quad \text{Eq. 9}$$

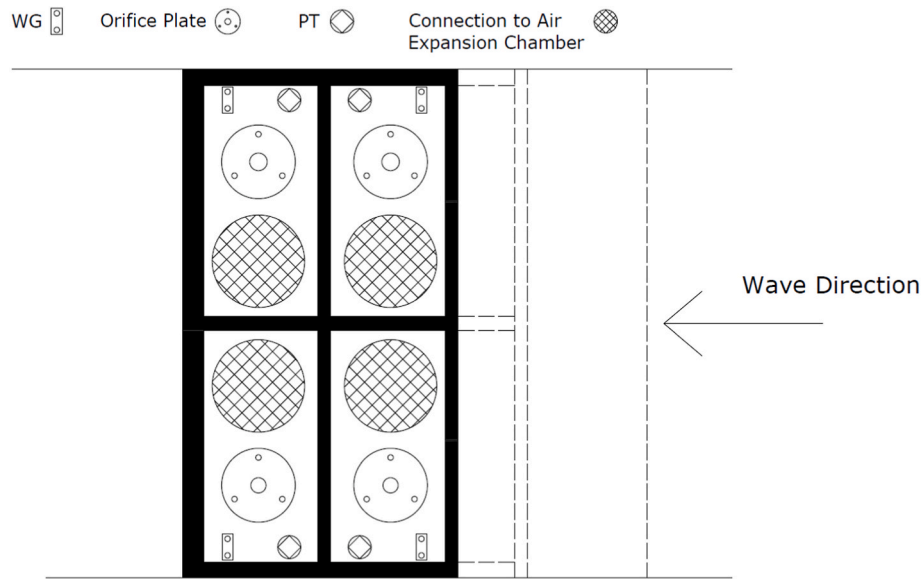


Fig. 5. Top view of the modular OWC roof, indicating the location of the wave gauges (WG), orifice plates, pressure transducers (PT), and air expansion chamber holes.

where κ is the polytropic exponent and δ is the density ratio (Falcão and Henriques, 2014). The air-compressibility model requires defining the polytropic exponent for both the model- and prototype-scale conditions. For the orifice-simulated PTO system, the model-scale polytropic exponent κ_m was taken as 1.0, following the recommendation of Falcão and Henriques (2014). In contrast, the prototype was scaled to represent a state-of-the-art turbine operating at an efficiency of $\eta \approx 0.6$, corresponding to a prototype polytropic exponent κ_p of approximately 1.2 (Falcão and Henriques, 2016; López et al., 2020).

The use of the external expansion chamber represents a deliberate distorted-similitude approach rather than a geometric representation of an additional prototype air volume. The OWC geometry is geometrically scaled, while the water-side dynamics, including the water depth and incident-wave conditions, are governed by Froude similitude. However, applying geometric scaling to the enclosed air volume does not simultaneously preserve the relative pneumatic restoring effect of the prototype air chamber. The effective air volume is therefore independently adjusted according to the thermodynamic similarity condition, so that the pneumatic compliance, and consequently the air-spring contribution to the coupled water-column response, is represented consistently at model scale. The external reservoir therefore provides the required adjustment of the effective air volume while leaving the geometrically scaled OWC and the prescribed Froude-scaled hydrodynamic conditions unchanged. Accordingly, this procedure is intended to preserve similarity of the dominant coupled hydrodynamic–pneumatic response rather than to reproduce every prototype-scale aerothermodynamic process; Reynolds-dependent airflow, heat-transfer processes and full-scale turbine aerodynamics remain subject to scale effects in a reduced-scale experiment (Falcão and Henriques, 2014; López et al., 2020).

The dual-chamber OWC was divided into front and rear compartments, and each chamber operated as an independent pneumatic circuit, equipped with its own expansion assembly consisting of a pair of steel barrels and the associated pipework. These two separate expansion systems preserved full pneumatic independence between the front and rear chambers while delivering the required reservoir capacity at model scale. Considering the geometric scale of 1:30 and a model–prototype water density ratio of $\delta = 0.98$, the required model-scale air volume V_m was then determined using the thermodynamic similarity criterion. To satisfy this requirement, the internal air cavity of the OWC model measuring 13.14 L was supplemented with an external expansion

reservoir, including the associated piping and connections, providing an additional 323.25 L of air volume for each pneumatic system. The desired total air volume was precisely achieved by partially filling the barrels with water to displace the excess air volume. Fig. 6 illustrates the configuration and physical connection of the external expansion chambers.

In the incompressible configuration, the expansion chamber was not connected. The necessary air holes were covered by blanking plates and sealed with silicone, and the resulting air volume was limited solely to the internal chamber volume, which follows the conventional geometric ε^3 scaling. This setup reflects conventional small-scale testing practice, where the air is treated as effectively incompressible, and density variations are neglected. Comparing these two methodologies allows for the quantification of the performance deviation caused by neglecting air compressibility; the specific mathematical formulation and resulting error analysis are detailed in Section 4.3.4.

3.5. Experimental programme

Experiments were conducted on five OWC configurations: Conventional OWC, U-OWC, L-OWC, DCOWC-1 and DCOWC-2 using a matrix of 23 regular wave conditions (17 constant-steepness, Wave Set 1, and 6 variable-steepness, Wave Set 2, cases). The experimental programme was conducted in two stages corresponding to incompressible (blanking) and compressible (expansion chamber connected) pneumatic conditions. In the incompressible (blanking) configuration, the air apertures of the chamber roof were sealed using a silicone-based gasket compound to ensure airtightness and prevent any pneumatic leakage during testing. In the incompressible configuration, orifice ratios of $Or = 0.8\%$, 1.2% , and 1.6% were applied to the Conventional OWC and DCOWC-1, whereas the L-OWC included an additional setting of 0.4% . The U-OWC and DCOWC-2 utilised a distinct set of $Or = 0.4\%$, 0.6% , 0.8% , and 1.2% , with the DCOWC-2 also employing a hybrid strategy pairing a 0.6% front orifice with a 1.2% rear orifice. For the compressible stage, the selection was adjusted to account for thermodynamic effects. The single-chamber geometries (Conventional, U-OWC, L-OWC) were tested with $Or = 0.4\%$, 0.8% , and 1.2% , while the dual-chamber structures (DCOWC-1, DCOWC-2) utilised $Or = 0.4\%$, 0.6% , 0.8% , and 1.2% . Additionally, the DCOWC-2 included optimised hybrid configurations, pairing a 0.4% or 0.6% front orifice with a 1.2% rear orifice. This systematic approach resulted in a total dataset of 792 experiments (384

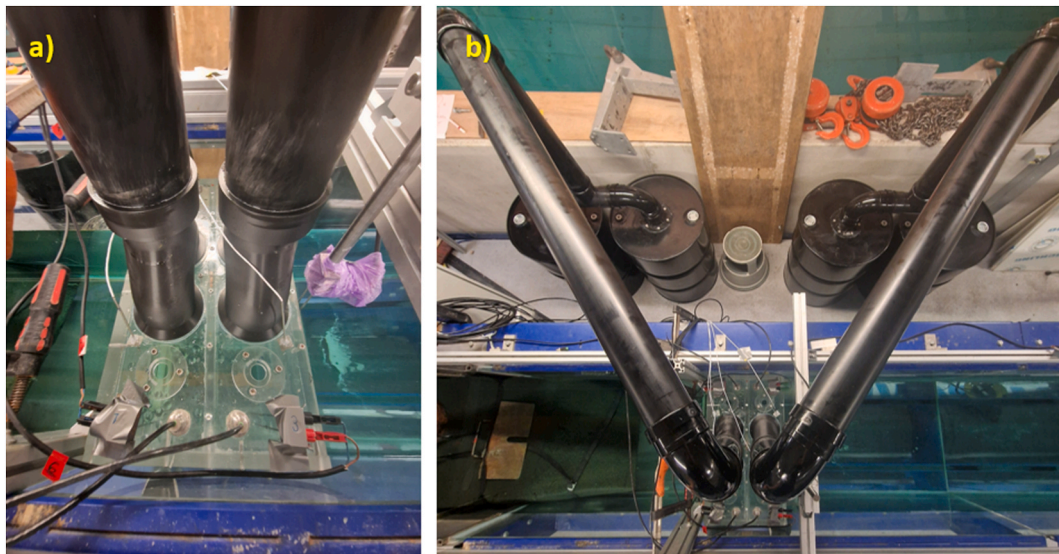


Fig. 6. (a) Close-up view of the rigid ducting connected to the OWC roof at the points of air expansion chamber connection; (b) Overview showing the pipes connecting the OWC model to the external steel barrel reservoirs.

incompressible and 408 compressible), forming a comprehensive basis for assessing the influence of geometry and air compressibility.

4. Results and discussion

This section presents the experimental findings regarding the hydrodynamic performance of the proposed OWC geometries. Although the individual hydrodynamic behaviour of the Conventional, U- and L-OWC has been documented in previous studies, those results were generally obtained across different facilities, geometric scales, pneumatic damping conditions and thermodynamic-scaling assumptions, preventing a direct, like-for-like comparison. Here, the three single-chamber geometries are examined to establish a directly comparable benchmark dataset, with all tests conducted within a single wave flume, at an identical geometric scale, under the same regular-wave conditions and using a common orifice-damping grid. This unified basis is essential for characterising the distinct resonance bandwidth, damping sensitivity, compressibility response and reflection behaviour of each single-chamber layout, and provides the physical reference needed to interpret the hydrodynamic coupling and mixed-damping strategy of the proposed hybrid dual-chamber configurations. The analysis provides a baseline comparison among the Conventional OWC, L-OWC and U-OWC designs, followed by the dual-chamber configurations. All configurations were investigated under a range of incident wave frequencies (B/L , where B is the chamber width and L is the wavelength) and damping ratios to identify optimal operating regions. Additionally, the present study examines the effects of air compressibility by comparing the results from the incompressible and expansion chamber configurations. In the presented figures, the legend nomenclature is defined as follows: The percentage values (e.g., 0.4%, 0.8%) correspond to the Or , which governs the pneumatic damping applied to the OWC chamber; lower ratios indicate higher damping. The marker style differentiates the wave testing conditions: solid markers represent trials with constant wave steepness, where both wave height (H_m) and period (T_m) were varied simultaneously while maintaining a constant wave steepness of $s_m = 0.02$ (Set 1). Conversely, hollow markers, labelled (var s_m), denote trials conducted at a constant wave height ($H_m = 0.06$ m, Set 2), resulting in variable wave steepness across the frequency range.

4.1. Hydrodynamic response: internal water surface elevation (RAO_c)

The hydrodynamic performance of the OWC is evaluated using the

Response Amplitude Operator (RAO_c) of the internal free surface elevation, defined in Equation (1). This metric quantifies the amplification of the water column motion relative to the incident wave. The experimental results for both single-chamber and dual-chamber configurations are presented in Figs. 7 and 8, respectively, comparing the incompressible and compressible datasets. For all single-chamber configurations (Fig. 7a–f), the water column response demonstrates a consistent inverse dependence on the dimensionless wave frequency. As the B/L ratio increases, corresponding to shorter wave periods, the RAO_c significantly decreases. Furthermore, the response magnitude was strongly governed by the pneumatic damping applied by the orifice. Larger Or settings (e.g., 1.6%) exhibit the highest RAO_c values due to the reduced damping constraints on the air volume, allowing for higher free-surface excursion. Conversely, the smallest Or (0.4%) imposes high pneumatic stiffness and damping, resulting in the lowest RAO_c across the tested range. For the Conventional OWC (Fig. 7a, b), a clear trend was observed when evaluating the effects of air compressibility. For relatively longer waves ($B/L < 0.042$), the incompressible configuration consistently yields slightly higher amplification than the compressible setup. However, this trend reverses for relatively shorter period waves ($B/L > 0.042$), where the compressible configuration demonstrates slightly higher response. In contrast to the Conventional OWC, the U-OWC and L-OWC (Fig. 7c–d and e–f) show responses to compressibility that are largely dependent on the damping magnitude. At lower damping levels (e.g., $Or = 1.2\%$), the RAO_c values for the incompressible and compressible configurations are nearly identical across the entire frequency range. However, when pneumatic damping is increased (e.g., $Or = 0.4 - 0.8\%$), the compressible configuration demonstrates a consistent, slight increase in response compared to the incompressible case for all frequencies.

The integration of OWCs into dual-chamber configurations results in a reduction of peak RAO_c compared to single chamber OWCs, attributed to the shielding and energy-sharing dynamics inherent to the coupled structures. However, the interaction effects differ noticeably between configurations, indicating that the hydrodynamic behaviour of specific geometries, particularly the L-OWC, is strongly modulated by the structure to which it is coupled. Similar to the single Conventional OWC, both chambers in the DCOWC-1 configuration exhibit a frequency-dependent crossover behaviour (Fig. 8a–d). This crossover represents the specific threshold where the behaviour of the air chamber reverses. For relatively longer waves, the incompressible configuration consistently yields slightly higher amplification than the compressible setup.

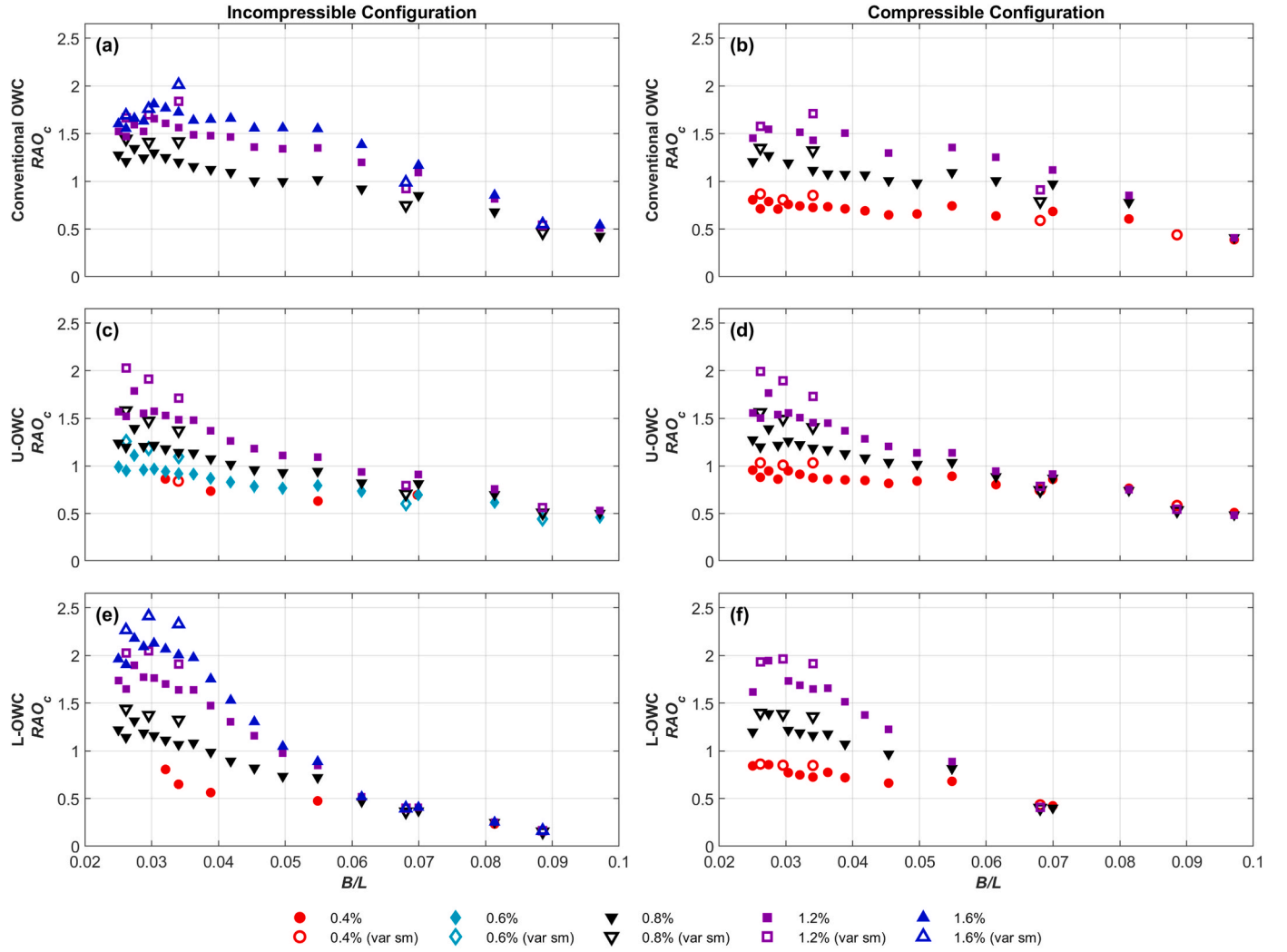


Fig. 7. Response amplitude operator RAO_c for single chamber OWC geometries: (a, b) Conventional OWC, (c, d) U-OWC, and (e, f) L-OWC. The left and right columns correspond to the incompressible and compressible configurations, respectively.

However, this trend reverses for relatively shorter period waves, where the compressible configuration demonstrates a slightly higher response. In this coupled system, a comparison between the incompressible (Fig. 8a-c) and compressible (Fig. 8b-d) results demonstrates that the air chamber acts as a damper for long waves but enhances the response for shorter waves. Notably, the L-OWC adopts this crossover trend when coupled in the DCOWC-1 configuration (Fig. 8c and d), deviating from its standalone behaviour. Conversely, in the DCOWC-2, which couples a U-OWC and L-OWC, the L-OWC behaviour shifts to align with the consistent enhancement pattern of the U-OWC (see Fig. 8e-h). In this case, the compressible configuration yields higher responses across the entire frequency range, particularly at high damping levels. The comparative analysis underscores a clear performance differentiation governed by pneumatic damping, wave frequency, and wave steepness. A general trend is observed where the water column response tends to increase as wave steepness decreases. Consequently, longer waves characterised by lower wave steepnesses drive larger amplification ratios compared to steeper, shorter waves. Within this context, the U-OWC demonstrates superior robustness under high pneumatic stiffness, maintaining the highest response across the widest bandwidth (Fig. 8e and f). The L-OWC is optimal specifically for the long-wave regime under low damping due to its long horizontal duct, but its performance degrades rapidly under high damping conditions (Fig. 8g and h).

Overall, the RAO_c results indicate that the influence of

compressibility is controlled by how strongly the pneumatic air spring interacts with the hydraulic inertia of each geometry. The expansion chamber increases the effective air volume and therefore reduces the air-spring stiffness, while the orifice ratio mainly controls the resistive PTO damping. In the Conventional OWC, the relatively short water path produces a moderate hydraulic inertance, so changing the air compliance causes a frequency-dependent shift in the balance between water-column inertia and pneumatic restoring force. This explains the crossover behaviour, where the incompressible configuration gives slightly higher amplification in longer waves, but the compressible configuration becomes more responsive in shorter waves. In the U-OWC, the vertical duct increases the effective oscillating water mass and introduces a coupled duct-chamber mode. Around this mode, small changes in air-spring stiffness modify both the amplitude and phase of the chamber pressure relative to the internal water oscillation, making the U-OWC more sensitive to compressibility, especially under high pneumatic resistance. By contrast, the L-OWC is governed mainly by the inertia of the long horizontal water slug, which shifts its main response toward the long-wave range and reduces the influence of air-volume scaling at its principal resonance. In the dual-chamber cases, the rear chamber response is additionally affected by shielding and by the phase of the transmitted wave field from the front chamber, explaining why the L-OWC follows a Conventional-type crossover in DCOWC-1 but a U-type enhancement trend in DCOWC-2. Therefore, the differentiated

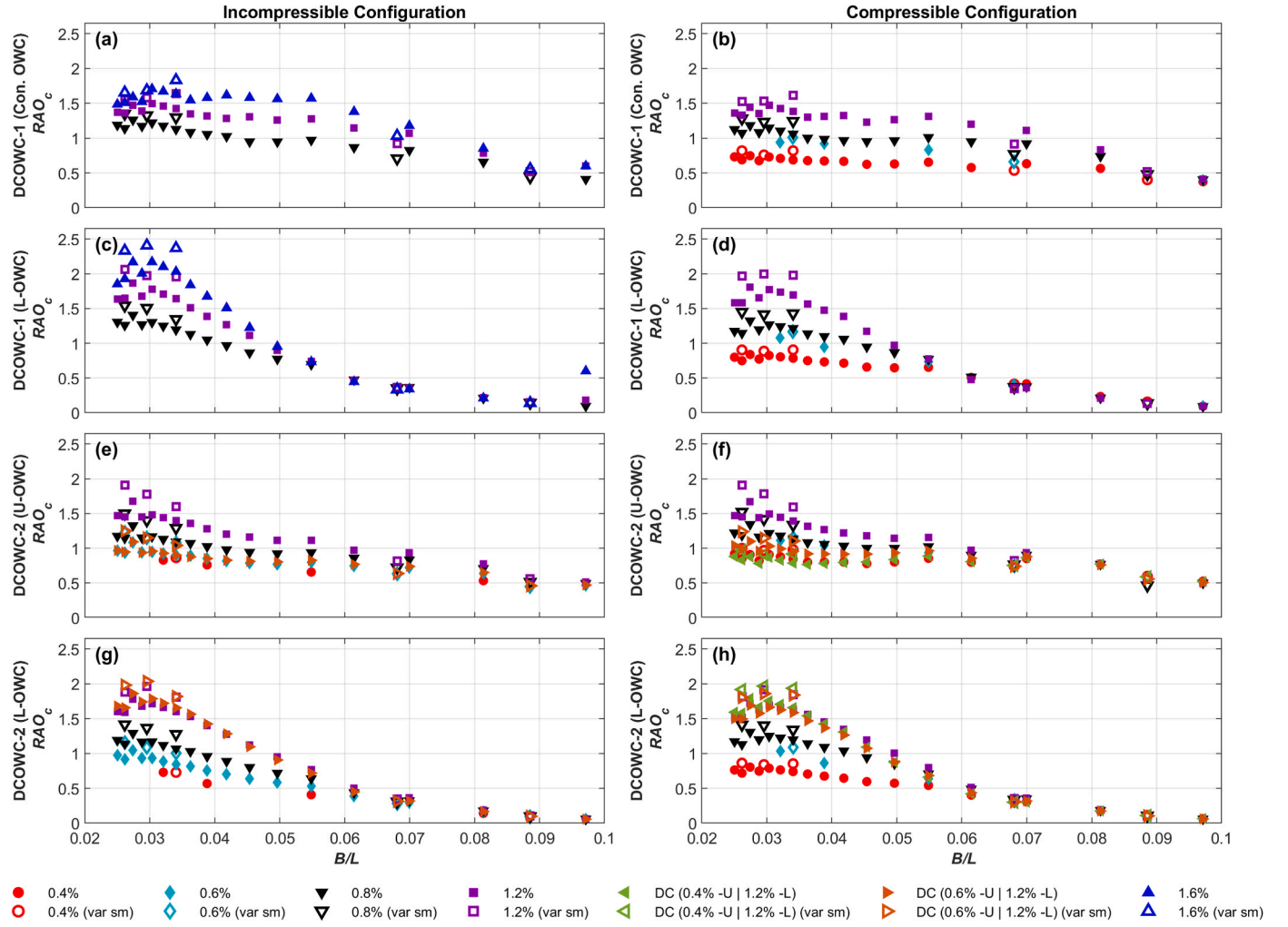


Fig. 8. Response amplitude operator RAO_c for individual compartments of dual-chamber systems: (a–d) DCOWC-1 (Conventional OWC and L-OWC) and (e–h) DCOWC-2 (U-OWC and L-OWC). The left and right columns display incompressible and compressible configurations, respectively.

RAO_c sensitivity across the tested configurations results from the combined effects of duct-induced hydraulic inductance, air-spring compliance and pressure–water-motion phase, rather than from air-pressure amplitude alone.

4.2. Pneumatic response: chamber air pressure oscillation (RAO_p)

The pneumatic performance of the OWC is characterised by the response amplitude operator of the chamber air pressure (RAO_p), defined in Equation (2). This metric quantifies the pressure fluctuation amplitude relative to the incident wave amplitude and is a primary driver of the power transmitted to the turbine. The pneumatic pressure response RAO_p is characterised by local maxima and parabolic variations rather than a monotonic increase or decrease (see Fig. 9 for single-chamber configurations and Fig. 10 for dual-chamber configurations). These response profiles vary significantly by geometry, with the Conventional OWC and U-OWC configurations displaying broader pressure amplification characteristics compared to the sharper, more focused response of the L-shape. Both the Conventional OWC (Fig. 9a, b) and U-OWC (Fig. 9c and d) demonstrate a dispersed pneumatic response, maintaining pressure amplification across a wider frequency band than the L-OWC. While they exhibit pronounced local variations such as the Conventional OWC showing secondary amplification around $B/L \approx 0.054$ and the U-OWC displaying a minor peak around $B/L \approx 0.069$, their most efficient operational range is distinctly concentrated in the

longer-period wave regime, with primary peaks occurring at $B/L \approx 0.03$. In contrast to the broader profiles of the previous structures, the L-OWC demonstrates a highly defined, unimodal pneumatic response (Fig. 9e and f). The pressure profile is characterised by a single, sharp peak centred at $B/L \approx 0.034$, which indicates a high degree of tuning for specific longer-period waves, lacking the secondary local maxima and broader bandwidth seen in the Conventional OWC and U-OWC geometries. A consistent compressibility-related trend is observed across all single-chamber geometries: the connection of the compressible chamber results in a decrease in the measured internal air pressure compared to the incompressible configuration. Notably, for the U-OWC under high damping conditions (see Fig. 9d), the compressible chamber configuration sustains relatively high pressure values from short-period waves ($B/L \approx 0.07$) extending into the long-wave regime ($B/L < 0.041$). This demonstrates that for the U-shaped geometry, high pneumatic damping effectively sustains high air pressure across the entire frequency spectrum when compressibility is correctly modelled. Comparing the structural performance shows distinct optimal regimes dependent on pneumatic damping. Under high damping conditions, the U-OWC demonstrates superior performance, maintaining higher pressure amplitudes across the frequency range compared to the other structures. For mid-range damping (e.g., $Or = 0.8\%$), the Conventional OWC exhibits higher RAO_p values than both the L and U shapes. However, in the long-period wave regime ($B/L < 0.041$) with moderate-to-large orifice ratios ($Or = 0.8\% - 1.2\%$), the L-OWC displays clear superiority,

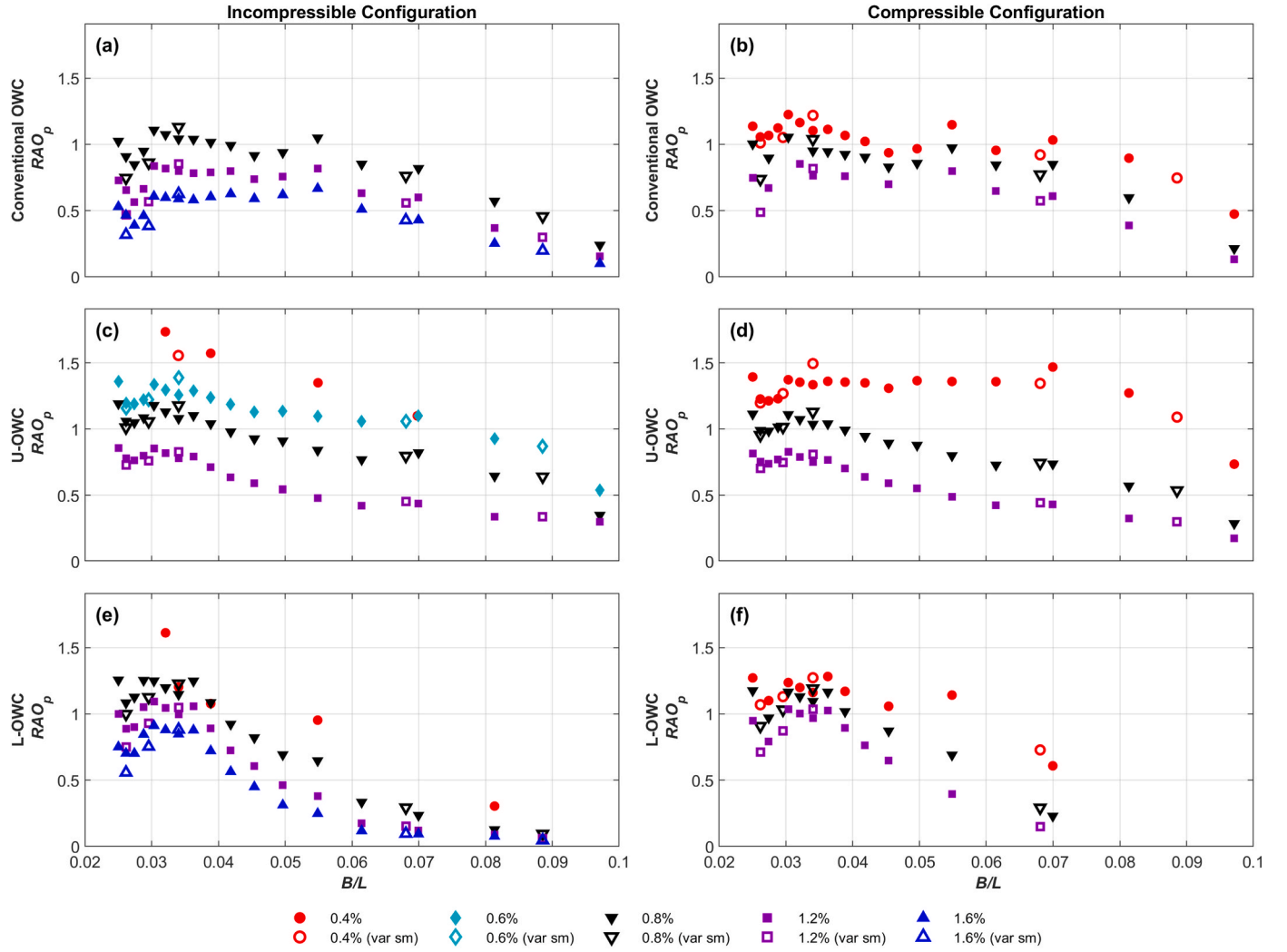


Fig. 9. Pneumatic response amplitude operator RAO_p for single chamber OWC geometries: (a, b) Conventional OWC, (c, d) U-OWC, and (e, f) L-OWC. The left and right columns correspond to the incompressible and compressible configurations, respectively.

confirming its effectiveness in tuning to low-frequency waves when pneumatic restriction is moderate.

The pneumatic response patterns of the dual-chamber configurations mirror those observed in the single-chamber tests, exhibiting similar frequency-dependent trends and peak locations. However, a consistent reduction on the order of 5–10% in pressure amplitude is observed across all compartments compared to their single chamber configurations (Fig. 10). This slight attenuation in peak values can be attributed to the hydrodynamic behaviour of the coupled system, where the connection of an additional OWC chamber extracts a portion of the incident wave energy, thereby distributing the total available pneumatic power between the two chambers rather than concentrating it in a single volume. The DCOWC-1 (Fig. 10a–d) reflects interaction effects where the Conventional OWC typically dominates the shorter wave and mid wave pneumatic response while the L-OWC contributes to longer waves. Similarly, in the DCOWC-2 configuration, the U-OWC (Fig. 10e and f) continues to show broad pneumatic bandwidth performance, while the L-OWC (Fig. 10g and h) maintains its characteristic shape with a reduced magnitude.

Taken together with the RAO_c results, the RAO_p response demonstrates how geometry-dependent water-column motion is converted into chamber-pressure fluctuation through the combined effects of pneumatic compliance and orifice resistance. Connecting the expansion chamber increases the effective air volume and softens the pneumatic air

spring. Consequently, for a comparable internal free-surface displacement, the compressible configuration generally produces a lower pressure amplitude than the blanked configuration. However, RAO_p should not be interpreted as a direct measure of energy-conversion efficiency, because pneumatic power also depends on the airflow rate and the phase relation between chamber pressure and oscillatory flow.

The geometry-dependent hydraulic-inertance mechanisms identified in the RAO_c analysis also influence the pressure response, but their effect on RAO_p appears primarily through changes in the pressure–water-motion phase relation. The relatively short internal flow path of the Conventional OWC produces a moderate shift in the pressure peak and response bandwidth when air compliance is changed. In the U-OWC, the longer curved duct introduces a coupled duct–chamber response that becomes particularly sensitive to air-spring compliance under high orifice resistance. By contrast, the long horizontal water slug of the L-OWC produces a sharper, low-frequency pressure peak and a more narrowly tuned response. In the dual-chamber systems, the pressure response is additionally modified by wave shielding, energy sharing and the phase and amplitude of the wave field transmitted from the front chamber to the rear chamber. The observed RAO_p differences therefore result from the combined effects of air-spring compliance, orifice resistance, hydraulic inertance and inter-chamber phase interaction.

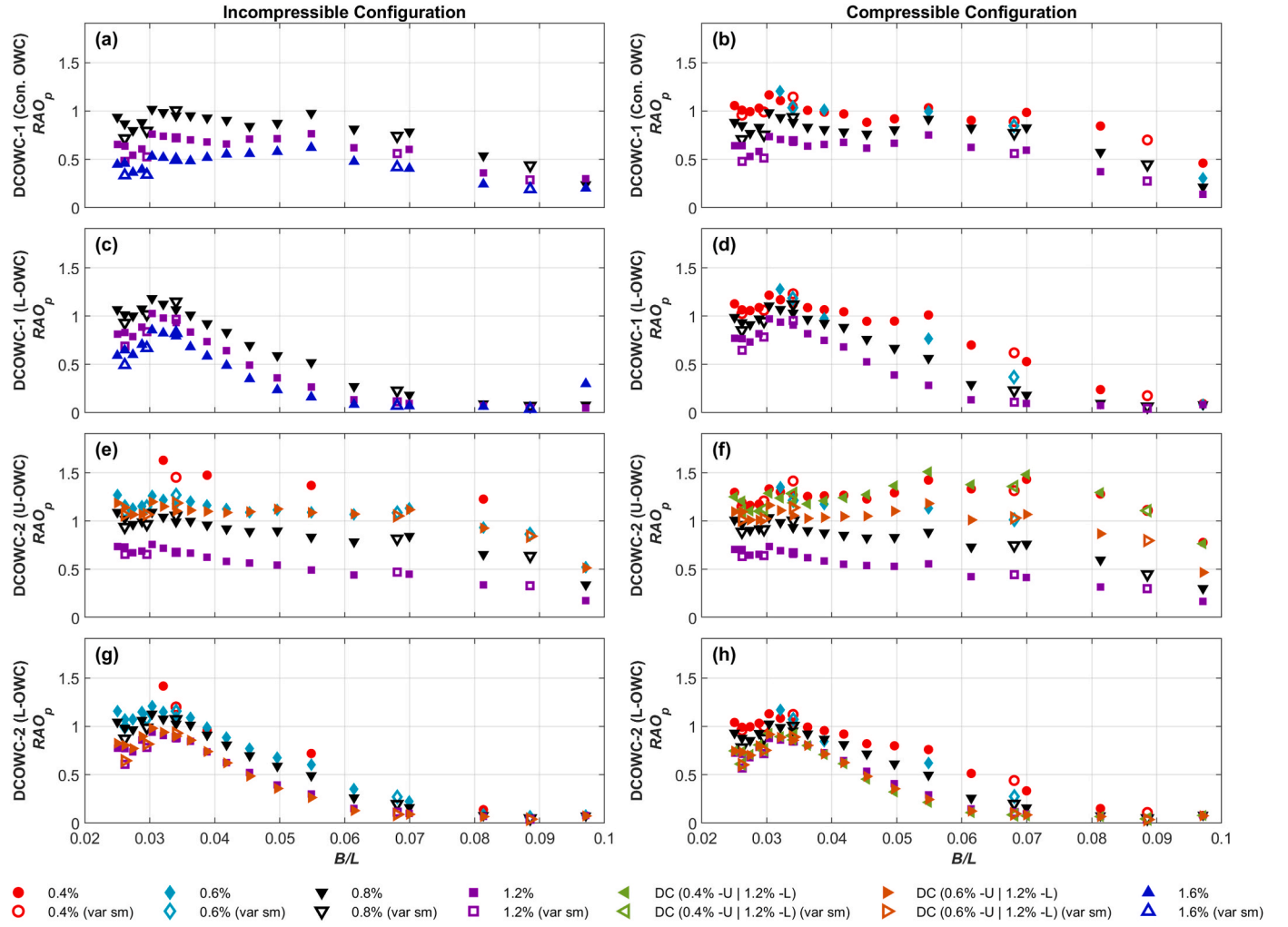


Fig. 10. Pneumatic response amplitude operator (RAO_p) for the individual chambers integrated into dual-chamber systems: (a, b) Conventional OWC in DCOWC-1; (c, d) L-OWC in DCOWC-1; (e, f) U-OWC in DCOWC-2; and (g, h) L-OWC in DCOWC-2. The left and right columns correspond to the incompressible and compressible configurations, respectively.

4.3. Energy absorption performance: capture width ratio (CWR)

The energy-capture efficiency of the OWC configurations is assessed using the capture width ratio (CWR), defined in Equation (5), which quantifies the fraction of incident wave power successfully absorbed by the pneumatic system. Maximising this metric requires optimal coupling between the chamber pressure and the air flow rate.

4.3.1. Single-chamber configuration performance

The CWR performance of the single-chamber configurations is presented in Fig. 11. The incompressible configuration of the Conventional OWC achieves a maximum efficiency at a dimensionless frequency of $B/L = 0.054$, reaching a peak CWR of 0.42 (see Fig. 11a). While the Or values of 0.8%, 1.2%, and 1.6% yield similar peak efficiencies, the $Or = 0.8\%$ setting demonstrates superior bandwidth in off-peak regions ($B/L < 0.03$ and $B/L > 0.07$). Enabling the compressible chamber configuration shifts the optimal peak to a higher frequency of $B/L = 0.07$ and increases the magnitude to 0.48 (see Fig. 11b), corresponding to a 12.5% increase. Although $Or = 0.8\%$ remains optimal for most of the spectrum, the higher damping of $Or = 0.4\%$ becomes superior in very short waves ($B/L > 0.08$).

The U-OWC exhibits a noticeably different behaviour compared to the Conventional OWC, characterised by a distinct sensitivity to pneumatic stiffness. In the incompressible configuration (see Fig. 11c), the

efficiency profile is dominated by high-damping conditions. The maximum CWR of 0.45 is observed at $B/L = 0.07$, where the $Or = 0.4\%$ and 0.6% settings yield nearly identical peak performance. While the high-damping cases excel at the peak, the moderate and low damping settings exhibit significantly reduced efficiencies, with values decreasing by approximately 25% and 50% respectively relative to the peak. Nevertheless, the moderate $Or = 0.8\%$ configuration marginally outperforms the others in the intermediate region ($0.036 < B/L < 0.05$). The compressible chamber configuration shows a pronounced amplification of these trends (see Fig. 11d). While high damping persists, the magnitude of power capture increases substantially. The $Or = 0.4\%$ case achieves a peak CWR of approximately 0.79 at $B/L = 0.081$, maintaining similarly high values (≈ 0.8) around $B/L = 0.07$. Comparing the two configurations reveals a substantial discrepancy, with the incompressible configuration underestimating the peak CWR by 43% for the high-damping case ($Or = 0.4\%$), whereas the corresponding underestimation was approximately 15% for the moderate-damping case ($Or = 0.8\%$). These results indicate that the U-OWC is highly sensitive to compressibility assumptions under high-damping conditions.

The L-OWC demonstrates a performance profile characterised by a sharp, focused resonant peak, distinguishing it from the broader bandwidths of the other geometries. In the incompressible configuration (see Fig. 11e), this peak occurs at a dimensionless frequency of $B/L = 0.034$, achieving a CWR of 0.44. Following this maximum, a distinct crossover

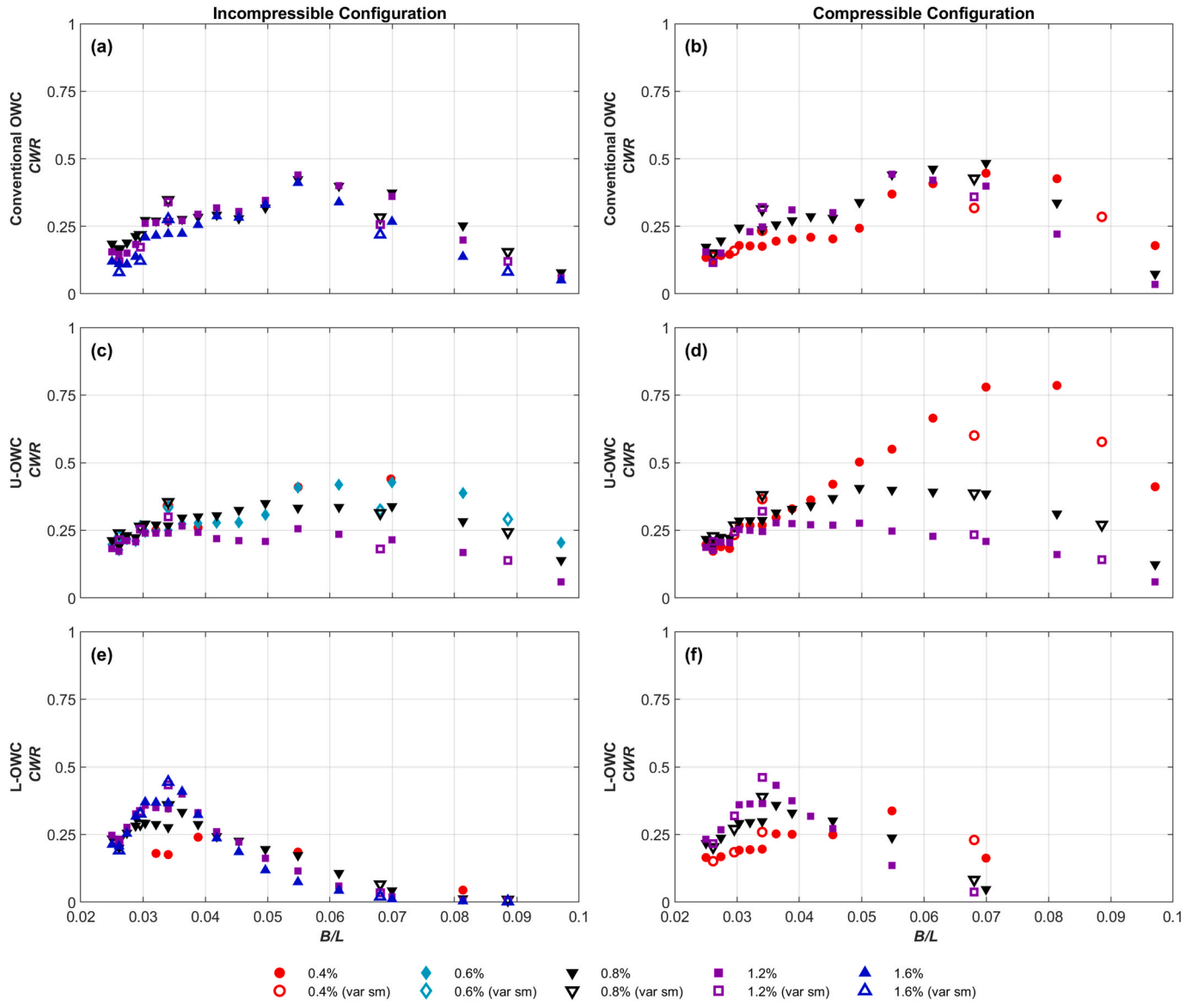


Fig. 11. Experimental Capture Width Ratio (CWR) for single-chamber OWC geometries: (a, b) Traditional OWC; (c, d) U-OWC; and (e, f) L-OWC. The left and right columns correspond to the incompressible and compressible configurations, respectively.

in damping efficiency is observed: for frequencies $B/L > 0.045$, the higher damping configurations ($Or = 0.4\%$ and 0.8%) yield higher efficiencies than the lower-damping settings ($Or = 1.2\%$ and 1.6%), indicating that higher pneumatic damping is required to maintain power extraction off-resonance. In addition, the compressible chamber configuration (see Fig. 11f) retains the primary characteristics of the incompressible case but with measurable enhancements. The peak CWR increases to 0.46, revealing that the incompressible baseline underestimated performance by 5.4%, while maintaining the same peak location at $B/L = 0.034$. This stability suggests that the primary low-frequency resonance is hydrodynamically driven. However, a unique compressibility effect is observed under high-damping conditions ($Or = 0.4\%$), where the primary response is significantly shifted to a higher frequency band rather than forming a new peak. Unlike the lower damping configurations, the $Or = 0.4\%$ setup demonstrates a delayed resonance, reaching its maximum CWR of 0.33 at a higher dimensionless frequency of $B/L \approx 0.055$. This different frequency shift is entirely absent in the incompressible configuration, demonstrating that correct compressibility modelling is essential for capturing the true resonant behaviour of highly damped systems. For the standalone L-OWC

compressible configuration, the three highest- B/L conditions ($B/L > 0.07$) were not tested because preliminary measurements indicated negligible energy capture ($CWR < 0.1$); however, this short-wave region was covered in the dual-chamber tests.

4.3.2. Dual-chamber configuration performance

The power conversion performance of the dual-chamber hybrids shows complex interaction effects where the coupling of water columns can lead to both energy shielding and localised efficiency enhancements depending on the geometry and thermodynamic configuration. To investigate the potential for synergistic operation, the study evaluates not only uniform damping conditions (where both chambers share identical orifice ratios) but also “mixed damping” strategies. As designated in Fig. 12 (e.g., DC 0.4%-U | 1.2%-L), these mixed configurations pair a highly damped front U-OWC ($Or = 0.4\%$) with a lower damping rear L-OWC chamber ($Or = 1.2\%$) to optimise the distinct resonance characteristics of each sub-structure.

In the DCOWC-1 configuration, the front Conventional OWC chamber (see Fig. 12a and b) demonstrates behaviour consistent with its single-structure characteristics but with notable magnitude deviations

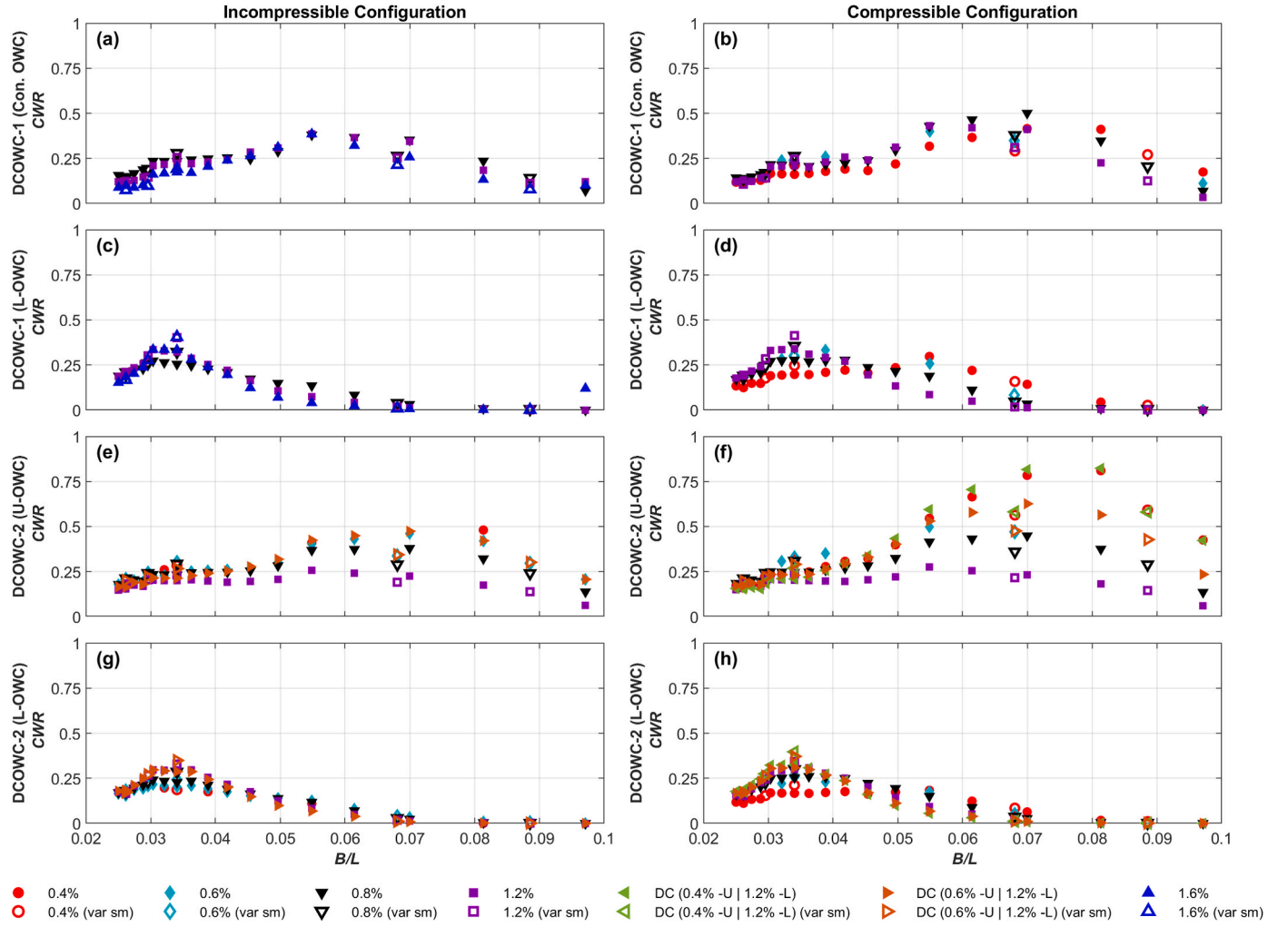


Fig. 12. Capture Width Ratio for individual chambers integrated into dual-chamber systems: (a, b) Conventional OWC in DCOWC-1; (c, d) L-OWC in DCOWC-1; (e, f) U-OWC in DCOWC-2; (g, h) L-OWC in DCOWC-2. The left and right columns correspond to the incompressible and compressible configurations, respectively.

due to interaction. In the incompressible configuration, the peak efficiency occurs at $B/L = 0.054$ with a CWR of 0.39. This represents an approximate 7% reduction compared to the single Conventional OWC baseline, attributable to the hydrodynamic coupling with the rear chamber. When the expansion chamber is connected, the peak shifts to $B/L = 0.07$, achieving a maximum CWR of 0.50. This represents a net efficiency increase of approximately 4% compared to the single chamber compressible peak. This counter-intuitive enhancement in the front chamber suggests a beneficial hydrodynamic interaction, where the coupled geometry creates a constructive interference pattern that amplifies energy capture despite the general shielding trend. The rear L-OWC (Fig. 12c and d) maintains its resonant frequency at $B/L = 0.034$. In the incompressible mode, the peak CWR is reduced to 0.40, representing a 9% decrease relative to the single chamber L-OWC due to the shielding effect. However, in the compressible mode, the efficiency marginally increases to 0.41. Although this corresponds to a nominal variation of approximately 2.5%, it suggests that the thermodynamic air spring effect partially counteracts the shielding losses by enhancing the restoring force on the water column.

The DCOWC-2 configuration highlights the superior adaptability of the U-OWC in array configurations. The front U-OWC (Fig. 12e and f) exhibits its peak response between $B/L = 0.07$ and 0.08 . In the incompressible mode, it achieves a CWR of 0.47 with the $Or = 0.4\%$ and 0.6% , representing a 4% efficiency increase over the single U-OWC incompressible baseline. This enhancement is even more pronounced in the

compressible configuration, where the peak CWR surges to 0.81 ($Or = 0.4\%$). This corresponds to a nominal variation of 2.5% over the single U-OWC result. Conversely, the rear L-chamber (Fig. 12g and h) in the DCOWC-2 setup performs less efficiently than it does in the DCOWC-1. The coupling with the highly resonant U-OWC results in significant energy loss, showing efficiency reductions of approximately 15% in the incompressible mode and 10% in the compressible mode compared to its performance in the DCOWC-1 configuration. Furthermore, the system's adaptability was tested using mixed damping methods (designated as DC 0.4%-U | 1.2%-L and DC 0.6%-U | 1.2%-L in the legend), where the front and rear segments were assigned different pneumatic loads. It was observed that the uniform damping and mixed damping cases led to similar results. For instance, considering the DC 0.4%-U | 1.2%-L case, the mixed scatter points in Fig. 12h (Rear L-OWC) correspond to the performance of $Or = 1.2\%$ and show only a slight change compared to the uniform $Or = 1.2\%$ case. Simultaneously, the data for the front U-OWC in Fig. 12f correspond to $Or = 0.4\%$ and coincide with the uniform $Or = 0.4\%$ baseline. This confirms that the damping of one chamber does not negatively disrupt the optimisation of the other one when compared with uniform damping scenarios. Overall, applying each chamber's optimal Or explicitly enhances the combined system output, a phenomenon that is clearly demonstrated in detail in Section 4.3.3.

4.3.3. Total power performance

The variation of this total metric (CWR_{total}) with respect to B/L

presented in Fig. 13 shows how the resonant characteristics of the coupled geometries combine to determine the overall system efficiency and bandwidth. The total response of the DCOWC-1 (L-OWC + Conventional OWC), shown in Fig. 13a and b, achieves the primary design objective of extending the operational bandwidth. In the incompressible configuration (Fig. 13a), the system attains a peak total CWR of approximately 0.65 at $B/L = 0.035$ for $Or = 1.2\%$. This peak is primarily driven by the rear L-OWC's resonance. As the frequency increases, the efficiency drops gradually, maintained by the secondary peak contributions from the front Conventional OWC chamber. The inclusion of the compressible configuration (Fig. 13b) smoothed the response curve significantly. While the peak CWR magnitude remains similar at approximately 0.65 (occurring at $B/L = 0.054$ with $Or = 0.6\%$), the damping dynamics shift in the shorter wave regime; specifically, for $B/L > 0.054$, higher damping settings ($Or = 0.4\%$ and 0.8%) exhibit superior performance when the efficiencies of the two chambers are aggregated. Consequently, the operational bandwidth is widened, with the device maintaining a total CWR exceeding 0.50 across a broad range from $B/L = 0.03$ to 0.07 . This broadband performance is a direct result of a double-peak pattern, where the low-frequency resonance of the L-OWC merges with the mid-frequency response of the Conventional OWC. This synthesis effectively mitigates the narrow-band limitations inherent to single-chamber devices, ensuring consistent power capture across a wider spectrum. Notably, this broadband-capture behaviour persists even when both chambers are operated under the same damping setting, confirming that the bandwidth gain is driven by the geometric pairing of the two resonance modes rather than by differential pneumatic tuning alone.

In addition, the DCOWC-2 (L-OWC + U-OWC), presented in Fig. 13c and d, exhibits a noticeably different performance profile, characterised by high peak power potential and superior broadband consistency. Even

under the incompressible assumption (Fig. 13c), the DCOWC-2 performs better overall than the DCOWC-1; while its low-frequency peak is marginally lower ($CWR \approx 0.60$ at $B/L = 0.034$), it sustains significantly higher efficiency into the high-frequency regime ($B/L > 0.054$), where the DCOWC-1 performance degrades. The compressible model (Fig. 13d) further amplifies this advantage, revealing the true potential of the configuration. The total capture width rises dramatically in the shorter wave regime, reaching a peak total CWR of approximately 0.85 at $B/L \approx 0.07$ with $Or = 0.4\%$. This is nearly 31% higher than the maximum achieved by the DCOWC-1. However, maximising extraction across the full spectrum requires reconciling the differing pneumatic requirements of the front and rear chambers. Crucially, the efficacy of the independent damping strategy is validated in both flow regimes. In the incompressible case (Fig. 13c), the mixed damping configuration (DC 0.6%-U | 1.2%-L), which assigns $Or = 0.6\%$ to the front U-OWC and $Or = 1.2\%$ to the rear L-OWC, explicitly follows the upper envelope of the efficiency curve. This confirms that the combination of higher damping for the front chamber and lower damping for the rear optimises the total output. Similarly, in the compressible case (Fig. 13d), the green scatter points (DC 0.4%-U | 1.2%-L), representing $Or = 0.4\%$ for the front U-OWC and $Or = 1.2\%$ for the rear L-OWC, consistently align with the peak efficiency values across the entire frequency range. This observation confirms that while uniform damping can achieve high peak values, the superior overall performance across the entire frequency spectrum is ensured by assigning each chamber its own optimal pneumatic load. The practical, energy-yield benefit of this broadband behaviour at a given site is, however, ultimately dictated by the local occurrence matrix; the wider the spread of dominant wave periods at the deployment location, the greater the potential cumulative annual gain over a narrow-band, peak-tuned single-chamber design.

The design strategy explicitly integrates the unique bandwidth

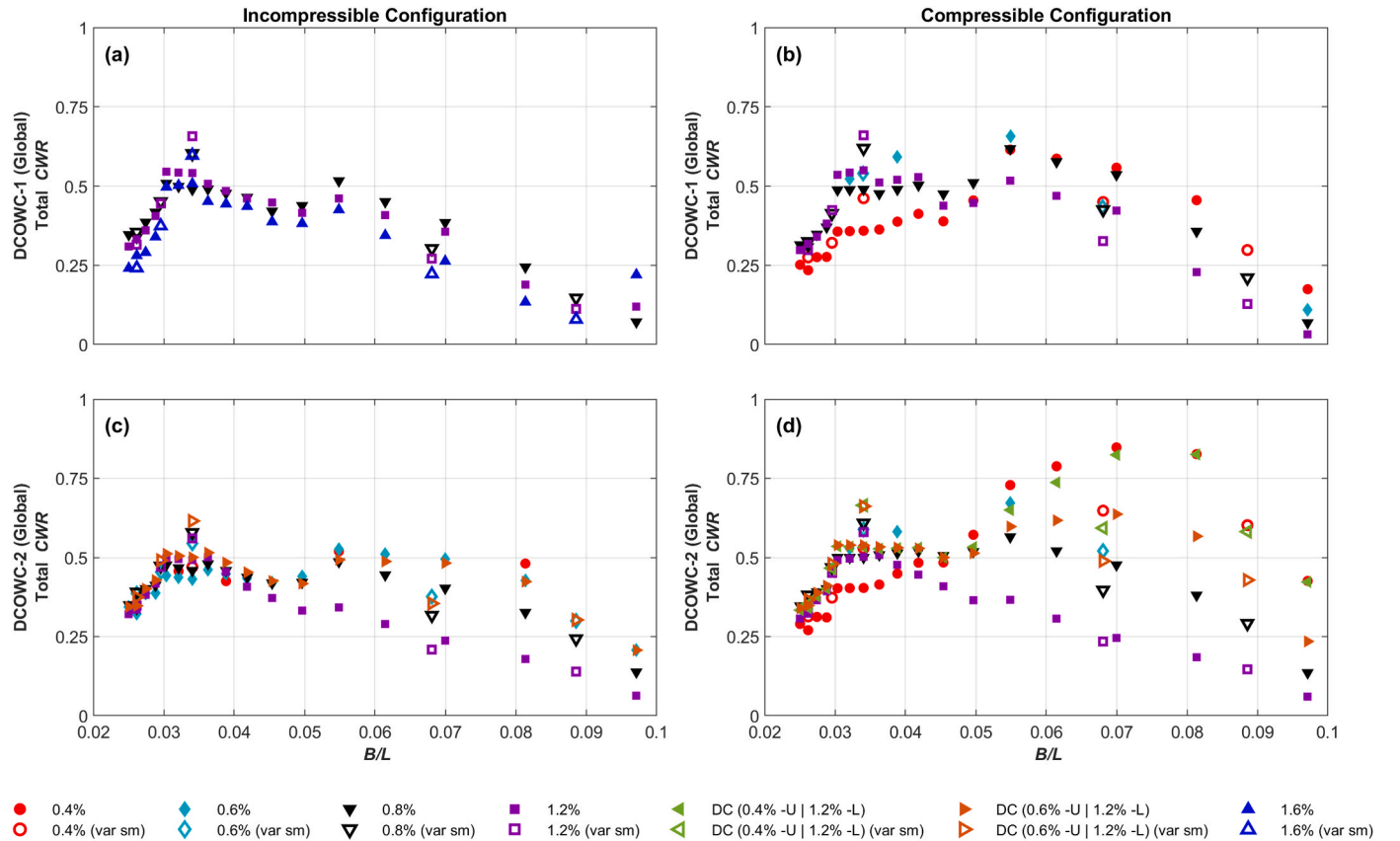


Fig. 13. Combined total CWR_{total} for the dual-chamber configurations, representing the sum of the front and rear chamber efficiencies. The left and right columns correspond to the incompressible and compressible configurations, respectively.

characteristics of the individual geometries, coupling the long-wave adaptive chamber to harness the high-energy components of the sea spectrum, while utilising short-wave adaptive components to create a flexible and broadband energy capture system. While every sea state possesses unique spectral characteristics, this hybrid geometry allows for site-specific optimisation via chamber pairing and pneumatic damping tuning. By integrating these complementary hydrodynamic responses into a compact dual-compartment structure, the device maximises energy extraction per metre of breakwater, demonstrating that structural hybridisation significantly upgrades power density and adaptability while respecting the spatial constraints of coastal infrastructure.

To assess the performance of DCOWC-2 beyond the internal DCOWC-1 baseline, its peak performance was compared with published dual-chamber OWC prototypes using reported CWR values or broadly comparable measures of hydrodynamic or primary efficiency. Because these measures are not strictly identical, the comparison should be regarded as indicative rather than as a direct ranking. The peak CWR of 0.85 obtained in the present study falls within the upper range reported for experimental dual-chamber OWCs. Gadelho et al. (2024) reported a peak primary efficiency of approximately 0.40 for a fixed onshore dual-chamber OWC, with reflection coefficients below 0.6 across the tested conditions. Yang et al. (2025) obtained a peak CWR of approximately 0.61 for a floating dual-chamber OWC, whereas Zhao et al. (2021) reported a peak CWR of approximately 0.56 for a dual-chamber breakwater, compared with 0.43 for the corresponding single-chamber configuration, together with two distinct resonant response regions. Mandev et al. (2024) achieved a peak CWR of 0.72 under the best-performing damping combination. Ning et al. (2024) reported that dividing the system into two chambers increased the peak efficiency from 0.86 to 0.98 and substantially broadened the effective operating bandwidth. Numerical studies have reported values of a similar order. Fu et al. (2023) obtained a maximum combined primary conversion efficiency of 76.3% for a land-based multi-chamber system, while Elhanafi et al. (2018) reported peak CWR values of up to 0.89 for offshore stationary dual-chamber OWCs. Mia et al. (2022) reported a peak efficiency of 0.33 for independent turbines, compared with 0.31 for a shared-turbine configuration, attributing the difference to phase mismatch between chamber responses. Taken together, these comparisons indicate that DCOWC-2 performs competitively relative to published dual-chamber systems. Its principal distinction lies in the deliberate combination of dissimilar chamber geometries within a single unit. Under the tested conditions, the front U-OWC contributes more strongly in the shorter-wave regime, while the rear L-OWC provides a complementary response in the longer-wave regime. This geometry-dependent interaction produces the observed double-peak response and broad effective operating bandwidth.

The parametric capture width ratio (CWR) evaluations demonstrate that the influence of air compressibility is profoundly geometry-dependent because each configuration imposes a unique streamline path on the oscillating fluid mass. Correct thermodynamic scaling, which increases the effective chamber air volume, serves to soften the pneumatic air-spring stiffness. Although a softer air spring may reduce the chamber-pressure amplitude, it can permit greater water-column motion and modify the phase relationship between chamber pressure and airflow, both of which influence the time-averaged pneumatic power. In a Conventional OWC, the streamline path is short, vertical, and direct; thus, the low fluid inertia results in a moderate resonance shift when correcting the air volume. In the U-OWC, the water follows a longer curved flow path through the vertical duct before entering the chamber, increasing the effective oscillating water mass and producing a coupled duct-chamber response. Near this coupled mode, the geometrically scaled air volume in the blanked configuration produces an overly stiff pneumatic response that restricts the internal water-column motion. Correct thermodynamic scaling increases the effective air volume, softens the pneumatic air spring and improves the pressure-flow

coupling, resulting in a higher CWR. In contrast, the L-OWC forces the water column through an extended horizontal streamline, creating a highly inertial water slug that shifts resonance to the very low-frequency wave regime. This response is comparatively less sensitive to air-volume scaling near its principal peak, although compressibility remains influential away from the principal response frequency and under high pneumatic damping. These geometry-dependent mechanisms also influence the dual-chamber systems, although their effects are modified by wave shielding, energy sharing and inter-chamber interaction. DCOWC-1 combines the long-wave response of the L-OWC with the intermediate-frequency response of the Conventional OWC, while DCOWC-2 combines the broader, compressibility-sensitive response of the U-OWC with the long-wave contribution of the L-OWC.

The differentiated optimal power take-off (PTO) damping behaviour across the U-OWC, Conventional, and L-OWC configurations is fundamentally governed by the balance between wave-induced excitation pressure at the chamber inlet and the system's total dynamic impedance. For the U-OWC, the vertical inlet duct opening is positioned close to the still water level (SWL) where wave-induced dynamic pressures are maximised. Although the curved internal flow path may introduce turning and flow-separation losses as the reciprocating water negotiates the 180° turn, the stronger near-surface excitation helps sustain the water-column motion under comparatively high orifice resistance. The experimental results therefore indicate that the U-OWC can maintain comparatively high chamber-air-pressure amplitudes and substantial airflow under the higher-damping conditions tested.

Conversely, the Conventional OWC requires a deeper front-wall draught to maintain an adequate hydraulic seal and prevent atmospheric air ingestion (broaching) under wave troughs. At this deeper submergence, the wave-induced dynamic pressure field decays exponentially with depth according to linear wave theory. Because the wave-induced excitation is weaker at this greater submergence and must also overcome flow-separation losses around the submerged front lip, high pneumatic damping strongly restricts the internal free-surface oscillations. Consequently, a larger orifice and lower pneumatic damping are required to sustain the oscillatory response and maximise primary energy capture under the tested conditions.

Finally, the L-OWC contains an extended horizontal conduit and a 90° elbow, which produce high hydraulic inertance and may introduce additional wall-friction, turning and flow-separation losses. Because the horizontal conduit produces high hydraulic inertance and added mass, additional orifice resistance further restricts the oscillatory water-column motion. This increases wave reflection and reduces the displacement of the horizontal water column, particularly in the low-frequency regime. Consequently, the best-performing condition for the L-OWC occurs with a relatively large orifice and low pneumatic damping, which reduces resistive losses and allows stronger oscillation of the inertial water column.

4.3.4. Quantification of thermodynamic scaling difference

The analysis of thermodynamic scaling error, presented in Fig. 14 for single-chamber geometries, demonstrates a clear alignment with the theoretical framework established in the literature, where the direction of error depends on the wave period (T) relative to the natural resonant period (T_r). For the Conventional OWC (Fig. 14a), which exhibits a natural resonance at approximately $B/L \approx 0.054$, the error curve demonstrates a clear polarity shift. At this specific resonant frequency, the difference is approximately 4% for the optimal $Or = 0.8\%$. However, this modest local deviation is misleading because the incompressible model fails to predict the frequency shift of the peak, resulting in a net underestimation of the true maximum potential by 12.5%. In the long-wave regime ($T > T_r$), corresponding to $B/L < 0.045$, the error is predominantly negative. This confirms that neglecting correct air-volume scaling leads to an overestimation of performance in long waves, consistent with findings by Elhanafi et al. (2017). Conversely, in the short-wave regime ($T < T_r$), the error transitions to positive values,

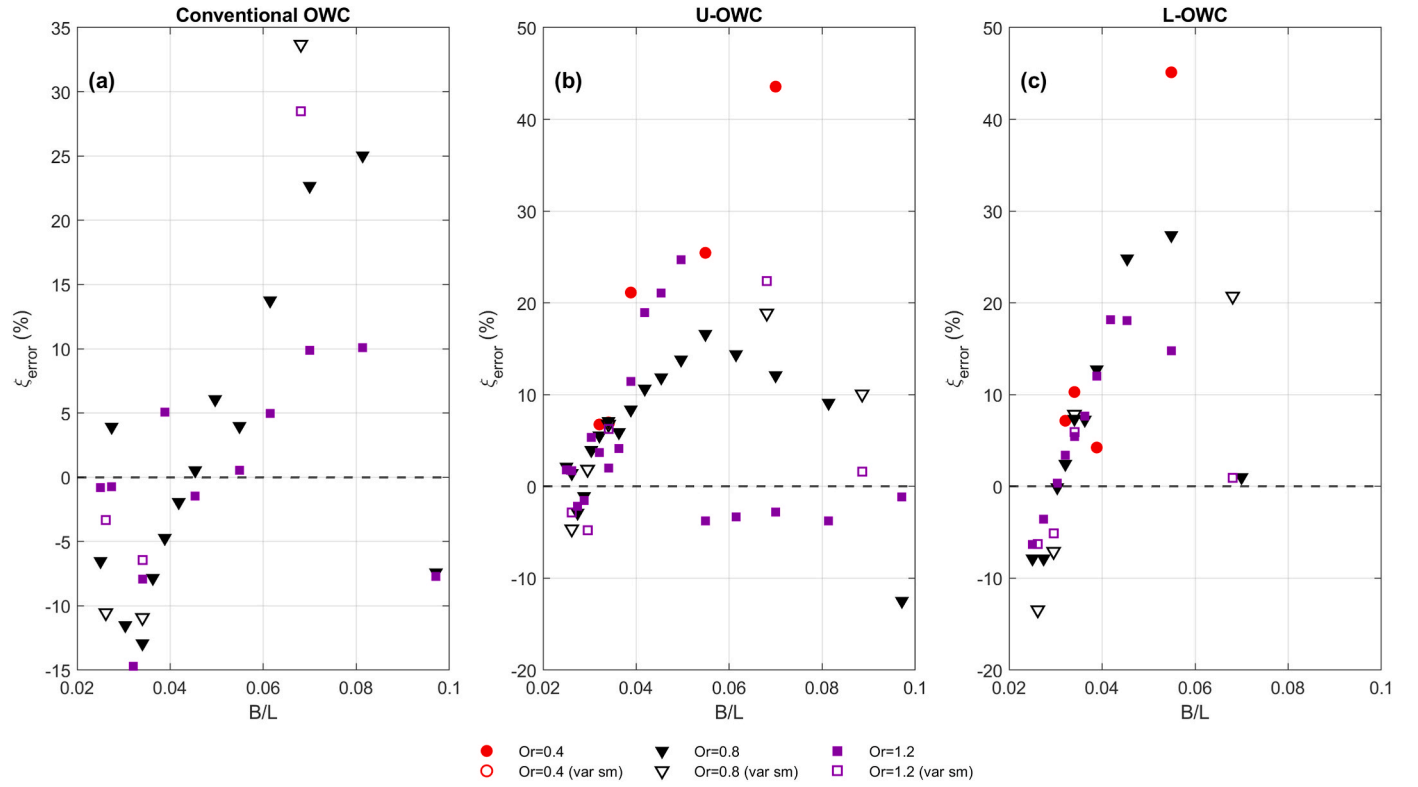


Fig. 14. Percentage scaling error (ξ_{error}) relative to the dimensionless wave frequency (B/L) for single-chamber configurations: (a) Conventional OWC; (b) U-OWC; and (c) L-OWC.

indicating an underestimation of the true power capture. This validates the premise that air compressibility acts as a critical restoring force at high frequencies, significantly enhancing water column oscillation.

The U-OWC geometry (Fig. 14b) demonstrates a different error profile that is strictly governed by the pneumatic damping ratio. In the long-wave regime corresponding to $B/L < 0.03$, the error is negative across all orifice ratios, confirming that neglecting correct air-volume scaling leads to a systematic overestimation of performance in long waves. However, the behaviour changes for $B/L > 0.03$ where the error becomes positive. It should be noted that the U-OWC does not exhibit the T_r dependent error profile, where the sign of the error is dictated by the resonant period threshold. For the high-damping case with $Or = 0.4\%$, the difference reached a maximum of 43% at $B/L \approx 0.08$, which also coincides with the resonance frequency. This underscores the critical role of the air spring in sustaining high-frequency oscillation against high pneumatic resistance. In contrast, the intermediate and low damping configurations exhibit a convex parabolic profile with a different peak location. For $Or = 0.8\%$, the peak error shifts to a lower frequency of $B/L \approx 0.054$ before decreasing. Similarly, the $Or = 1.2\%$ case reaches its peak difference at $B/L \approx 0.054$ again. However, the $Or = 1.2\%$ behaviour is unique, as the compressibility difference becomes negligible for $B/L > 0.054$. This indicates that as the pneumatic restriction decreases, the airflow becomes unconstrained, rendering the thermodynamic spring effect less critical to the system's dynamics. Consequently, while the high-damping configuration fails to model resonance correctly, the low-damping configuration remains robust with minimal error in the high-frequency regime. The L-OWC (Fig. 14c) demonstrates a different error profile. While robust with low deviation at its primary low-frequency resonance ($B/L \approx 0.034$), it exhibits a sharp spike in error at higher frequencies, reaching approximately 45% at $B/L = 0.054$. In the long-wave regime ($T > T_r$), corresponding to $B/L < 0.03$, the error is negative. This confirms that neglecting correct air-volume scaling leads to an overestimation of performance in longer waves, while the opposite trend is observed for $B/L > 0.03$.

The analysis extends to the dual-chamber configurations presented in Fig. 15, where the interaction between chambers influences the thermodynamic scaling error. For the L-OWC and Conventional OWC integrated into DCOWC-1 and DCOWC-2 (Fig. 15a, b, and d), the error profiles largely mirror the frequency-dependent polarity shifts observed in the single chambers. In the long-wave regime, these chambers exhibit negative scaling errors, indicating an overestimation of performance by the incompressible model. As the frequency increases towards the short-wave regime, the error transitions to positive values, reaching peaks of 30–40% near resonance. This confirms that, for these geometries, the incompressible approximation produces frequency-dependent performance errors, with underestimation at higher frequencies and overestimation in the long-wave regime. However, the front U-OWC within the DCOWC-2 (Fig. 15c) demonstrates a noticeably different pattern characterised by a predominantly positive error across the entire frequency range, reaching a peak underestimation of 40%. Unlike the other geometries, it does not exhibit a distinct region of significant negative error in long waves; instead, the incompressible model consistently underestimates the power capture capability of this chamber.

To elucidate the physical origin of this systematic underestimation, the system's time-domain response is analysed in Figs. 16 and 17. These specific cases were selected to contrast a regime where thermodynamic error is significant against a control case where it is negligible. In the high-damping analysis presented in Fig. 16 ($Or = 0.4\%$), the chamber pressure response shows a clear deviation in amplitude at the waveform peaks. The incompressible model overpredicts the chamber-pressure peaks while underpredicting the internal free-surface motion observed in the compressible configuration. This indicates that correct air-volume scaling softens the pneumatic air spring, relaxing the constraint at the air–water interface and allowing larger water-column motion despite lower pressure amplitudes. Fig. 17 presents the time-domain response for the U-OWC in DCOWC-2 at $Or = 1.2\%$. In this specific configuration, the thermodynamic scaling difference is practically negligible. The agreement between the two models is very close, with the

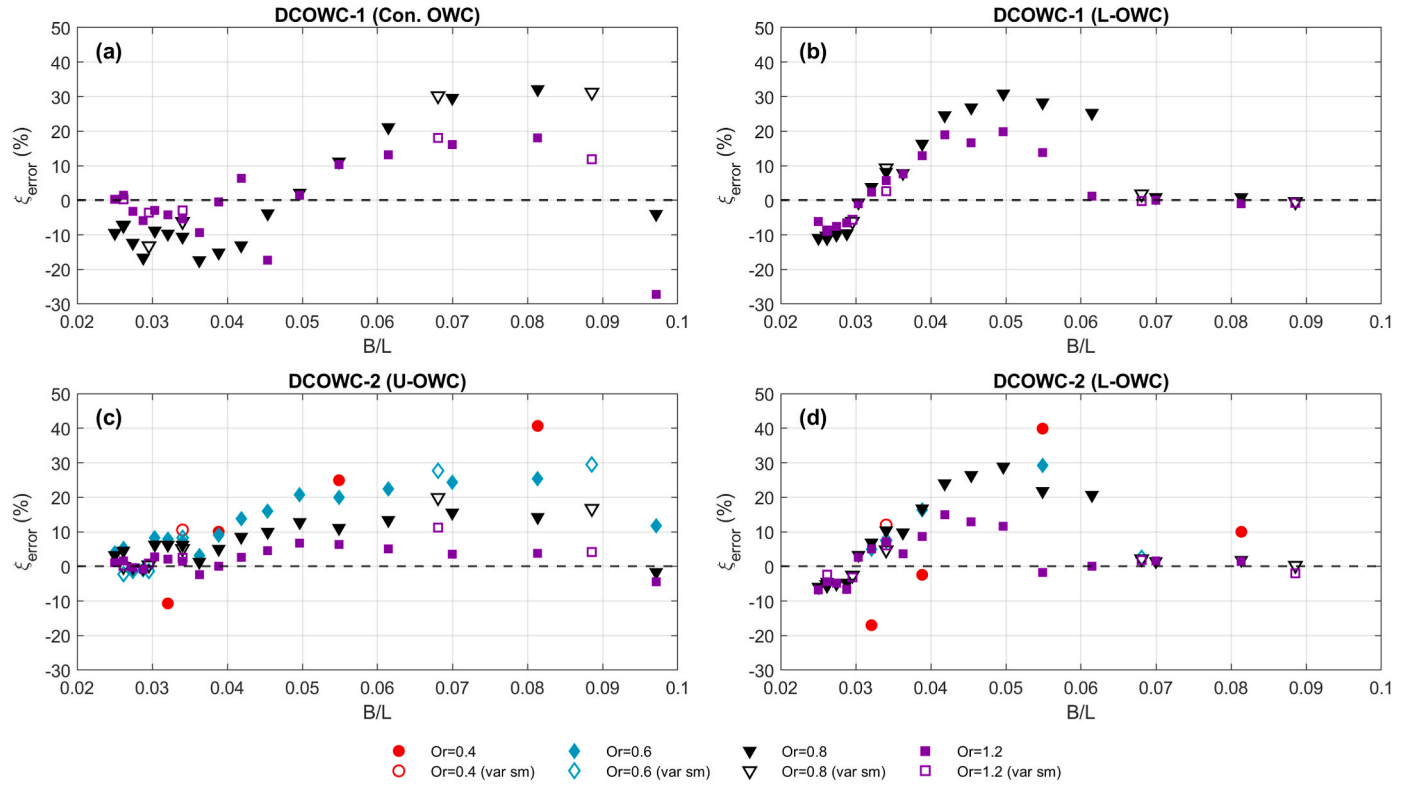


Fig. 15. Percentage scaling error (ξ_{error}) for individual chambers within dual-chamber arrays: (a) Conventional OWC in DCOWC-1; (b) L-OWC in DCOWC-1; (c) U-OWC in DCOWC-2; and (d) L-OWC in DCOWC-2.

incompressible data points nearly overlapping the compressible curves across the selected wave periods.

Taken together, these results explain the wide range of thermodynamic-scaling errors observed across the tested configurations. The largest discrepancies occur under high pneumatic damping, reaching 43% for the single U-OWC near resonance and approximately 45% for the L-OWC away from its principal low-frequency response. By contrast, the Conventional OWC exhibits a smaller peak deviation but a clear frequency-dependent change in the sign of the error. Thermodynamic-scaling error therefore cannot be represented by a constant correction factor, because both its magnitude and direction depend on chamber geometry, pneumatic damping, and operating frequency.

The geometry-dependent trends arise from the interaction between pneumatic air-spring compliance and the hydraulic inertance of the internal water column. In the Conventional OWC, the relatively short and direct internal flow path produces moderate hydraulic inertance. Correcting the effective air volume therefore causes a comparatively moderate change in the response magnitude but produces a clear frequency-dependent shift in the sign of the scaling error. In the U-OWC, the vertical duct creates a longer internal flow path, a greater effective oscillating water mass and a coupled duct-chamber response. This makes the system particularly sensitive to changes in air compliance under high orifice resistance. In the L-OWC, the extended horizontal water path and large inertial water slug produce a different frequency-dependent response, with comparatively small scaling error near the principal low-frequency peak but a pronounced deviation at higher frequencies. The observed errors therefore reflect the combined effects of air-spring compliance, geometry-specific hydraulic inertance and the phase relation between chamber pressure and airflow.

To isolate the influence of pneumatic damping on the compressibility response, the U-OWC chamber within DCOWC-2 was selected for time-domain analysis because it exhibits a large thermodynamic-scaling difference at $Or = 0.4\%$, but an almost negligible difference at $Or = 1.2\%$.

These contrasting cases represent a compressibility-sensitive high-damping condition and a lower-damping control condition, respectively. Under high pneumatic damping, $Or = 0.4\%$, Fig. 16 shows clear differences between the compressible and blanked responses of the U-OWC chamber within DCOWC-2. Correct air-volume scaling generally produces larger internal free-surface oscillations but lower chamber-pressure amplitudes. Increasing the effective air volume reduces the pneumatic air-spring stiffness and permits greater water-column motion, which increases the swept air volume and associated airflow. It also modifies the phase relation between airflow and chamber pressure. Because time-averaged pneumatic power depends on the cycle-integrated product of pressure and airflow, the increase in airflow and the change in pressure-flow phasing can outweigh the reduction in chamber-pressure amplitude, resulting in a higher CWR. Under lower pneumatic damping, $Or = 1.2\%$, Fig. 17 shows much closer agreement between the compressible and blanked time histories, with only minor differences in internal free-surface elevation and chamber-pressure response. The larger orifice limits chamber-pressure build-up and reduces the influence of the pneumatic air spring on the coupled water-column motion. The contrast between Figs. 16 and 17 therefore demonstrates that the influence of air compressibility depends strongly on pneumatic damping. More broadly, the thermodynamic-scaling effect is governed by the interaction among pneumatic damping, chamber geometry, hydraulic inertance and pressure-flow phasing, rather than representing a uniform correction across all OWC configurations.

4.3.5. Influence of wave steepness on efficiency

While the incident wave period determines the primary resonance condition, the magnitude of energy capture is strongly modulated by wave steepness. Experimental results indicate that when the wave condition aligns with the structure's resonant period and simultaneously exhibits low steepness, hydrodynamic efficiency is significantly enhanced by approximately 20–25%, as observed in Fig. 11e, f at $B/L = 0.034$ for the L-OWC. Conversely, steeper waves near resonance

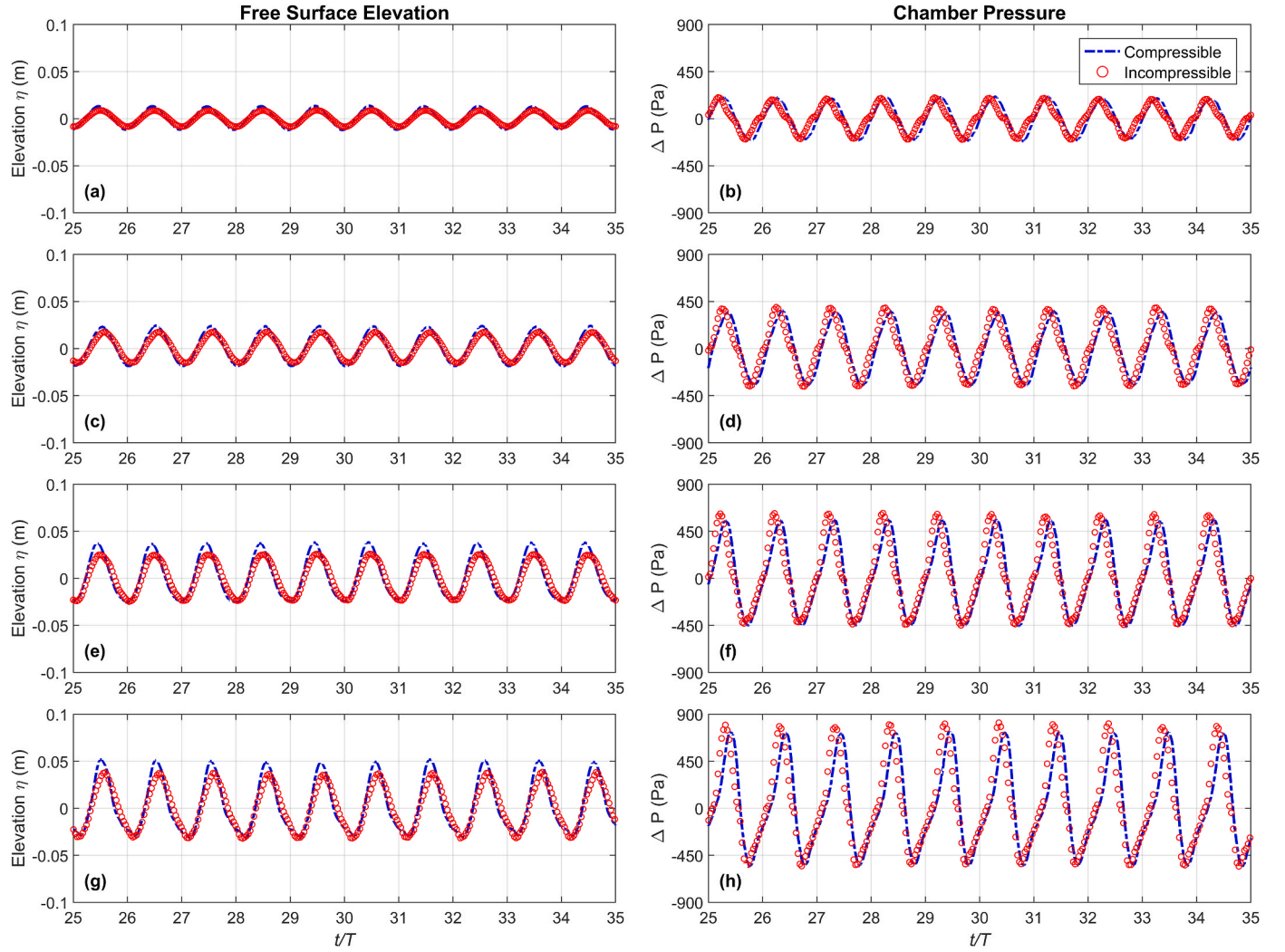


Fig. 16. Time-history response of free surface elevation (left) and chamber pressure (right) for the U-OWC chamber in the DCOWC-2 array ($Or = 0.4\%$). Wave conditions: (a, b) $H_m = 0.0329$ m, $T_m = 1.05$ s ($B/L = 0.08$); (c, d) $H_m = 0.0488$ m, $T_m = 1.35$ s ($B/L = 0.055$); (e, f) $H_m = 0.07$ m, $T_m = 1.75$ s ($B/L = 0.04$); and (g, h) $H_m = 0.0835$ m, $T_m = 2.05$ s ($B/L = 0.032$). Comparisons between incompressible (solid red) and compressible (dashed blue).

induce greater non-linear turbulence and viscous dissipation at the submerged lip, thereby suppressing the peak CWR . This effect is clearly visible for the Conventional OWC in Fig. 11b at $B/L = 0.068$, as well as for the U-OWC in Fig. 11c, d at the same frequency. Consequently, the primary dataset (Set 1), obtained at a constant steepness of $s_m = 0.02$, should be viewed as a conservative baseline. Lower steepness values (e. g., $s_m < 0.02$), which are typical of clean swell conditions, would be expected to yield significantly higher CWR values. This sensitivity underscores the importance of accounting for wave steepness in performance reporting; the extremely high CWR values achievable under low-steepness conditions could be misleading if the target deployment site is characterised by a rougher, steeper wave climate. Importantly, however, while a lower steepness would increase the magnitude of efficiency, the fundamental frequency-dependent trends and the specific B/L locations of the resonant peaks remain consistent with the current findings.

4.4. Wave reflection characteristics (C_R)

The hydrodynamic efficiency of an OWC breakwater is fundamentally linked to its wave-reflection characteristics. Since transmission through the breakwater is negligible, a reduction in the reflection coefficient C_R indicates that a larger fraction of the incident wave energy interacts with the OWC system rather than being reflected seaward. The

reflection coefficients presented in Fig. 18 for the single-chamber geometries exhibit pronounced frequency-dependent behaviours governed by their specific resonant properties and pneumatic damping. A consistent trend is observed across the single-chamber geometries: smaller orifice ratios, corresponding to higher orifice resistance and pneumatic damping, are generally associated with higher reflection coefficients across most of the tested frequency range. The increased pneumatic resistance restricts internal free-surface motion and reduces the amount of incident-wave energy entering the chamber, thereby increasing reflection. Conversely, larger orifice ratios reduce pneumatic resistance and generally lower C_R near the principal response frequency by permitting stronger internal water-column motion.

For the Conventional OWC, the relationship between C_R and CWR varies between the incompressible and compressible configurations, as presented in Fig. 18a and b. In the incompressible case, the lowest reflection coefficient is observed at $B/L \approx 0.054$. At this frequency, reflection drops to approximately 0.55 for optimal damping ratios, coinciding closely with the peak CWR . This alignment indicates that maximum efficiency in the incompressible configuration is driven purely by impedance matching at the structure's natural frequency; when the structure absorbs the most energy, it reflects the least back to the sea. However, the compressible chamber configuration introduces a notable decoupling effect between reflection minima and efficiency

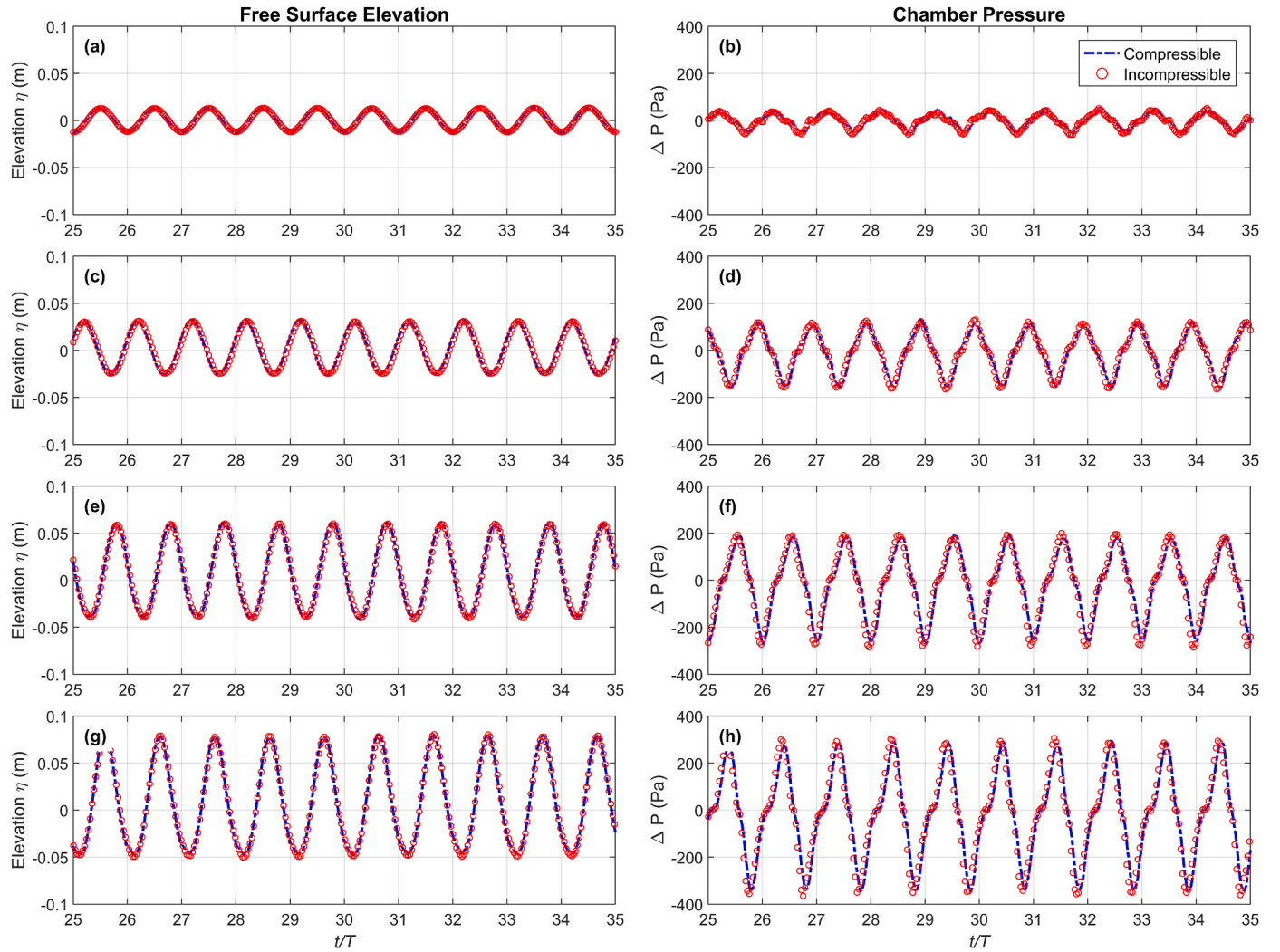


Fig. 17. Time-history response of free surface elevation (left) and chamber pressure (right) for the U-OWC chamber in the DCOWC-2 array ($Or = 1.2\%$). Wave conditions: (a, b) $H_m = 0.0329$ m, $T_m = 1.05$ s ($B/L = 0.08$); (c, d) $H_m = 0.0488$ m, $T_m = 1.35$ s ($B/L = 0.055$); (e, f) $H_m = 0.07$ m, $T_m = 1.75$ s ($B/L = 0.04$); and (g, h) $H_m = 0.0835$ m, $T_m = 2.05$ s ($B/L = 0.032$). Comparisons between incompressible (solid red) and compressible (dashed blue).

maxima. While the peak CWR shifts to a higher frequency regime around $B/L \approx 0.07$, the reflection coefficient trends themselves remain unchanged compared to the incompressible case when observing identical orifice ratios. Specifically, the lowest reflection coefficient remains anchored near $B/L \approx 0.054$, and the magnitude of C_R for a given damping condition does not vary significantly between the incompressible and compressible setups. This suggests that the compressible chamber's primary hydrodynamic impact is not to alter the wave reflection at the front wall, but rather to enhance the internal air compressibility via the softer air spring. This allows the water column to oscillate and absorb energy efficiently at higher frequencies ($B/L \approx 0.07$) even though reflection values ($C_R \approx 0.6$ – 0.7) are not at their absolute minimum.

Following the Conventional OWC, the L-OWC geometry demonstrates a pronounced shift in reflection behaviour toward the lower frequency spectrum (Fig. 18e and f). In both incompressible and compressible configurations, the L-OWC exhibits its most effective reflection suppression at $B/L \approx 0.035$, a resonant point significantly lower than the minimum observed for the Conventional OWC. Such a shift can be attributed to the extended water column path of the L-geometry, which increases the effective fluid mass and naturally lowers the resonant frequency. The reflection characteristics are highly sensitive to pneumatic damping; larger orifice ratios ($Or = 1.2\%$ and 1.6%),

corresponding to lower pneumatic damping, produce lower reflection coefficients, with C_R dropping below 0.55 near resonance. Conversely, the high-damping case ($Or = 0.4\%$) maintains a high reflection coefficient ($C_R > 0.75$) across the entire frequency range, indicating that high pneumatic resistance restricts the long-period resonant motion required for efficient L-OWC operation. The U-OWC geometry exhibits the most complex reflection behaviour among the single structures, characterised by a unique damping-dependent resonance (see Fig. 18c and d). Unlike the Conventional OWC and L-OWC geometries, where reflection minima remain anchored at fixed frequencies, the U-OWC minimum shifts significantly based on pneumatic stiffness. Specifically, low damping ($Or = 1.2\%$) targets low frequencies ($B/L \approx 0.035$), whereas high damping ($Or = 0.4\%$) shifts the effective absorption range to high frequencies ($B/L \approx 0.07$). Crucially, this additional local reflection minimum at $B/L \approx 0.07$ coincides strongly with the peak capture width observed in the compressible configuration. This alignment confirms that the high-frequency efficiency peak is driven by a separate resonant mode activated by stiff pneumatic damping. Consequently, the U-OWC offers a dynamic operational profile unlike those of fixed-resonance structures and can be tuned to different wave conditions by adjusting the turbine damping, which is parameterised here by the orifice ratio.

The reflection coefficients for dual-chamber configurations are presented in Fig. 19. DCOWC-1 configuration exhibits reflection

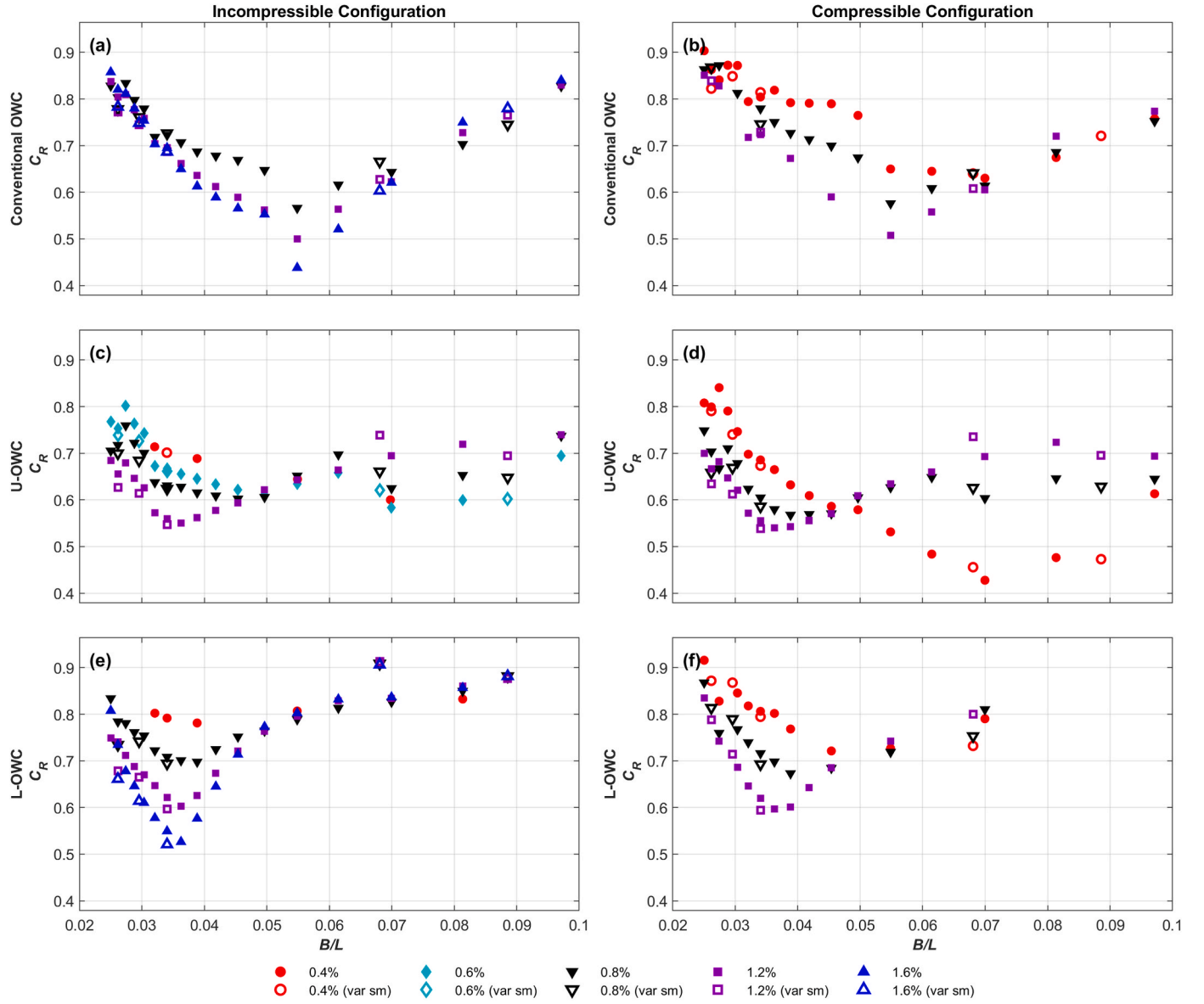


Fig. 18. Wave Reflection Coefficient (C_R) for single-chamber OWC geometries: (a, b) Conventional OWC; (c, d) U-OWC; and (e, f) L-OWC. The left column corresponds to the incompressible configuration, and the right column corresponds to the compressible configuration.

characteristics that are strongly influenced by the hydrodynamic interaction between the front Conventional OWC chamber and the rear L-shaped chamber (see Fig. 19a and b). In the incompressible configuration, the system achieves its lowest reflection coefficient of approximately $C_R \approx 0.34$ at a non-dimensional frequency of $B/L \approx 0.039$ (specifically for the $Or = 1.6\%$ damping ratio). This minimum is notably lower than the best performance observed for the single Conventional OWC, which only reaches a minimum of $C_R \approx 0.44$ at $B/L \approx 0.054$. Furthermore, the DCOWC-1 reflection trough is broader and deeper than that of the single L-OWC, which reaches a similar minimum but within a narrower bandwidth centred at $B/L \approx 0.035$. The dual-chamber coupling effectively bridges the operational gap between the low-frequency L-type and the mid-frequency Conventional type, resulting in an intermediate resonant bandwidth that suppresses reflection more effectively than either single structure alone in this transition region. In the compressible configuration of the DCOWC-1, the wave reflection behaviour is clearly dominated by the rear L-shaped chamber (Fig. 19b). As observed in the single structure analysis, the single L-OWC exhibits a reflection minimum at approximately $B/L \approx 0.036$, whereas the single Conventional OWC resonates at a significantly higher frequency of B/L

$L \approx 0.054$. When these geometries are coupled in the DCOWC-1, the resulting reflection minimum occurs at $B/L \approx 0.038$. This value is close to the single L-OWC natural frequency. Furthermore, the DCOWC-1 demonstrates a general trend of superior reflection suppression compared to the single modes. DCOWC-2 demonstrates superior broadband reflection suppression, particularly when employing the proposed “mixed damping” strategy (Fig. 19c and d). A direct comparison shows the significant advantage of the dual-chamber setup over the single structures. The single U-OWC (with high damping, 0.4%) exhibits a sharp reflection minimum at high frequencies ($B/L \approx 0.07$) but reflects strongly at low frequencies ($C_R > 0.7$ for $B/L < 0.03$). Conversely, the single L-OWC excels at low frequencies ($B/L \approx 0.035$) but loses efficacy as the frequency increases. DCOWC-2 mixed damping case (DC 0.4% -U + 1.2% -L) overcomes these individual limitations by effectively combining their strengths. It maintains a reflection coefficient consistently below 0.5 across a vast frequency range from $B/L = 0.035$ to $B/L = 0.09$. This flat reflection profile is significantly lower than the average reflection of either single structure across the same bandwidth, confirming that the DCOWC-2 successfully integrates the wave-absorbing properties of the L-OWC (low frequency) and U-OWC (high

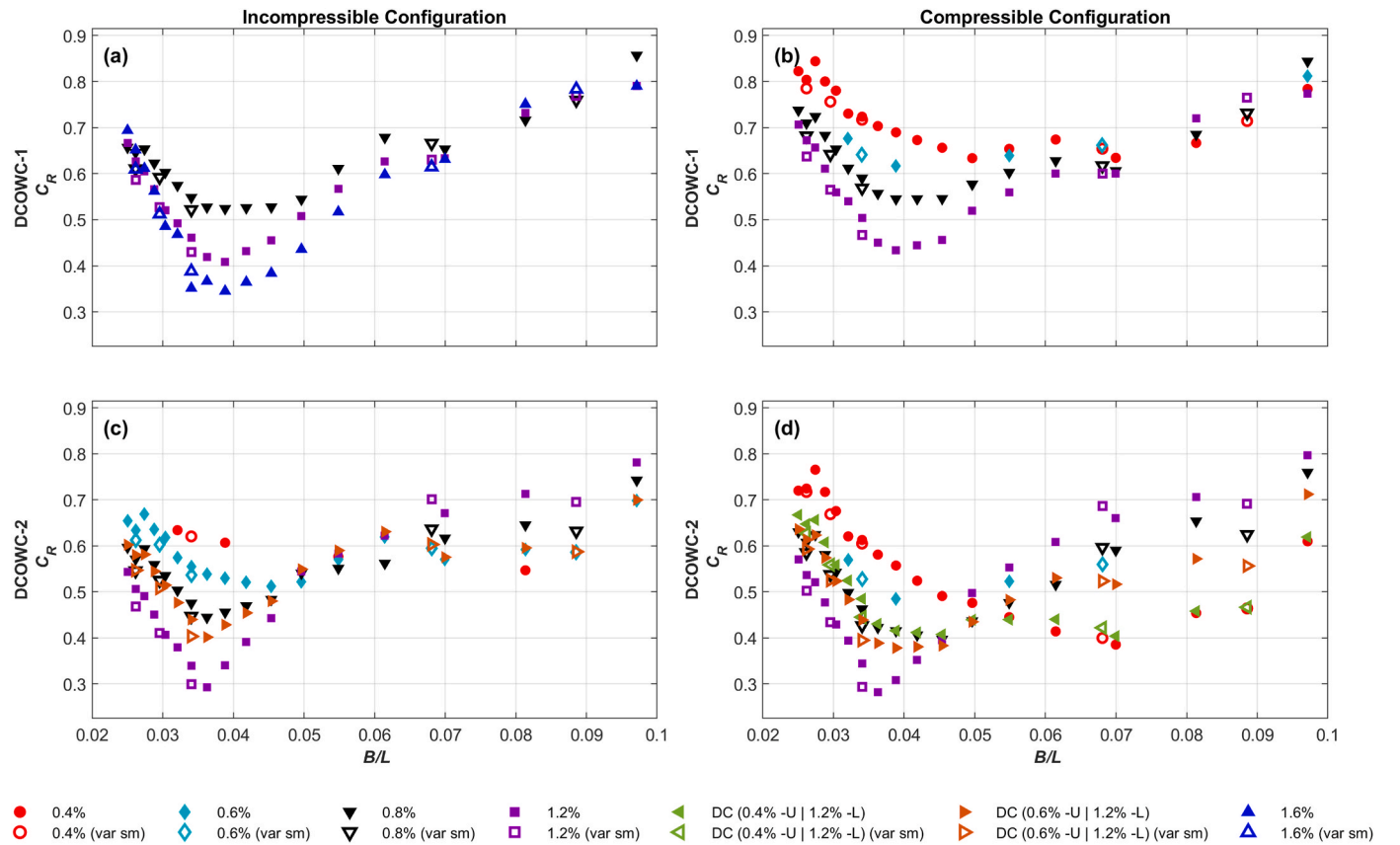


Fig. 19. Wave Reflection Coefficient (C_R) for dual-chamber systems: (a, b) DCOWC-1 (Conventional and L-OWC); and (c, d) DCOWC-2 (U-OWC and L-OWC). The left and right columns display the incompressible and compressible configurations, respectively.

frequency) to create a globally more absorbent structure that minimises wave reflection more effectively than any single chamber. These reflection characteristics compare favourably with published dual-chamber prototypes operating as breakwaters. The consistently low, broadband reflection of DCOWC-2 ($C_R < 0.5$ across $B/L = 0.035$ to 0.09) falls within, or below, the ranges reported for comparable devices. Gadelho et al. (2024) reported reflection coefficients remaining below 0.6 across all tested damping conditions on their onshore dual-chamber device, while Ning et al. (2024) showed that dual-chamber coupling suppresses reflection more effectively than an equivalent single chamber, most markedly for short waves, with the reflection coefficient reaching a minimum of $C_R \approx 0.2$ to 0.3 near resonance. Zhao et al. (2021) similarly identified reduced reflection, together with a wider effective bandwidth, as the principal advantage of multi-chamber over single-chamber breakwaters. The present results are consistent with these findings and extend them: rather than suppressing reflection only at a single resonant frequency, the asymmetric U to L pairing of DCOWC-2 lowers reflection across a broad frequency band, combining the low-frequency absorption of the L-chamber with the high-frequency absorption of the U-chamber. This confirms that the hybrid geometry reinforces the coastal-protection function of the structure across a wide range of sea states, an outcome not attainable with a single-geometry chamber.

The main physical insight from the reflection analysis is that broadband reflection suppression is achieved through geometry-specific pneumatic damping rather than through uniformly high or low damping. For most configurations, larger orifice ratios and lower pneumatic damping reduce C_R near the principal response frequency because the airflow is less restricted and stronger internal water-column motion can be sustained. This behaviour is particularly evident in the L-OWC, where the high hydraulic inertance of the extended horizontal water column

requires relatively low damping to maintain its long-wave response. Under high orifice resistance, the internal free-surface motion is restricted and a larger proportion of the incident-wave energy is reflected. The U-OWC exhibits a different damping-dependent response, with high pneumatic damping producing a local reflection minimum in the shorter-wave range under the tested conditions. The mixed-damping strategy in DCOWC-2 exploits these complementary characteristics by applying high damping to the front U-OWC to reduce short-wave reflection and lower damping to the rear L-OWC to maintain long-wave absorption. The broad and comparatively flat C_R response of DCOWC-2 therefore results from the combined effects of geometry-dependent hydraulic inertance, orifice-controlled pneumatic resistance and interaction between the front and rear chambers.

Beyond its energy-capture implications, reduced reflection may improve the coastal-protection performance of an OWC breakwater by weakening the seaward standing-wave field and reducing wave agitation in front of the structure. However, the associated effects on structural loading, toe scour, overtopping and sediment transport were not measured in the present experiments and require dedicated investigation under irregular waves and site-specific bathymetric conditions.

5. Conclusion

This study presented a comprehensive experimental investigation into the hydrodynamic optimisation and scaling fidelity of five OWC configurations: three single-chamber geometries (conventional, U-OWC, and L-OWC) and two novel dual-chamber hybrid systems (DCOWC-1 and DCOWC-2). Through a systematic testing program comprising 792 tests under regular wave conditions, the research quantified the performance benefits of geometric hybridisation and evaluated the critical influence of air compressibility using a correct thermodynamic scaling

approach (ϵ^2) versus the traditional incompressible method (i.e., Froude number-based scaling).

The comparative analysis of the single-chamber structures showed divergent, frequency-dependent performance envelopes driven by their specific RAOs. The L-OWC exhibited a sharp, unimodal pressure response focused at low frequencies ($B/L \approx 0.034$), making it ideal for capturing long-period swell energy but limiting its operational bandwidth. Conversely, the U-OWC and Conventional OWC demonstrated broader pneumatic amplification effective in the intermediate-to-short wave regimes. Notably, the U-OWC demonstrated superior individual performance over a broad operating bandwidth, achieving a peak CWR of 0.79. However, the results highlighted that while single chambers can be tuned efficiently for specific sea states, they inherently suffer from limited bandwidths and high susceptibility to wave reflection off-resonance.

The integration of single-chamber geometries into dual-chamber hybrids successfully overcame these limitations. The DCOWC-1 (Conventional + L-OWC) extended the operational bandwidth by merging the low-frequency response of the L-chamber with the mid-frequency response of the conventional chamber, achieving a stable total capture width ratio (CWR) of approximately 0.65. However, the DCOWC-2 (U-OWC + L-OWC) emerged as the superior configuration, achieving a large total peak efficiency of 0.85 in the compressible configuration. This represents an approximate 31% improvement over the DCOWC-1. Component-level analysis revealed that this performance is not merely additive but constructively coupled; the U-OWC sub-chamber achieved a higher efficiency within the array than in a single configuration (up to a 4% increase), proving that the dual-chamber layout actively enhances the hydrodynamic response of its constituent parts. These findings confirm that the complementary coupling of a long-wave tuned L-OWC with a highly resonant U-chamber maximises energy extraction per unit width of the breakwater.

Another critical finding of this study is the validation of the mixed-damping strategy for the dual-chamber configuration. DCOWC-2 achieved its optimal performance by assigning high pneumatic damping ($Or = 0.4\%$) to the front U-OWC and lower pneumatic damping ($Or = 1.2\%$) to the rear L-OWC. This front-rear damping allocation is physically consistent with the distinct hydrodynamic characteristics of the two chambers. The front U-OWC, with its near-free-surface vertical duct opening, receives strong wave-induced excitation and can sustain substantial chamber-pressure response under high damping. The rear L-OWC, by contrast, requires lower pneumatic resistance to preserve the oscillation of its long horizontal inertial water column and maintain its long-wave response.

The mixed-damping configuration also provided favourable wave-reflection characteristics, maintaining a reflection coefficient (C_R) below approximately 0.5 across a broad frequency range ($B/L \approx 0.035$ – 0.09). Together with the corresponding CWR results, this indicates that independently tuning the pneumatic resistance of the two chambers can simultaneously support broadband energy capture and favourable external wave–structure interaction. These findings highlight the importance of chamber-specific pneumatic tuning when optimising OWC systems intended for integration within coastal breakwaters. Furthermore, sensitivity analysis regarding wave steepness identified a clear general trend where hydrodynamic efficiency is inversely correlated with steepness. Consequently, the results presented herein ($s_m = 0.02$) likely represent a conservative baseline, with consistently higher efficiencies expected under the lower steepness conditions typical of clean swells, while the fundamental frequency-dependent trends remain unchanged.

Finally, the comparison between the incompressible and compressible configurations confirmed that neglecting air compressibility introduces substantial systematic errors in performance prediction. The U-OWC was most sensitive to thermodynamic scaling, with the incompressible configuration underestimating the peak CWR by 43%. The Conventional OWC also demonstrated a 12.5% efficiency deviation and

a frequency shift in peak performance. These results demonstrate that neglecting correct air-volume scaling can produce substantial geometry, damping- and frequency-dependent errors, including both under-prediction and overprediction of OWC performance.

The regular-wave analysis presented in this study provides a controlled foundation for identifying the governing hydrodynamic and thermodynamic mechanisms of the single- and dual-chamber OWC configurations, including resonance behaviour, pneumatic-damping sensitivity, chamber-to-chamber interaction and air-compressibility effects. However, the peak CWR values and operating bandwidths obtained under monochromatic excitation should not be interpreted as direct estimates of annual energy capture under natural sea states. Irregular ocean waves contain broadband spectral energy distributions and wave-group variability, so the energy-capture response may differ under unimodal and bimodal conditions. The present results should therefore be interpreted as controlled frequency-response benchmarks rather than as complete predictions of random-sea performance. Structural survivability and extreme-wave loading were not assessed in the present campaign and require dedicated investigation under irregular, grouped and extreme-wave conditions. The same OWC configurations will be examined in a subsequent study under unimodal and bimodal spectra using spectral and energy-weighted performance metrics.

CRedit authorship contribution statement

Gunay Gazaloglu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hasan Gokhan Guler:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **John Ashlin Samuel:** Supervision, Methodology, Conceptualization. **Keri Collins:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **David Simmonds:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interests

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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Data availability

Data will be made available on request.

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