



Research paper

Seakeeping analysis of catamaran and barge floats for floating solar arrays: A CFD study with experimental validation

Binjian Ou^a, Burak Can Cerik^{a,b,*}, Luofeng Huang^{a,*}

^a Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, MK43 0AL, United Kingdom

^b Department of Naval Architecture and Ocean Engineering, Inha University, Incheon, 22212, South Korea

ARTICLE INFO

Keywords:

Floating solar
Hydrodynamics
Computational fluid dynamics
Multi-body dynamics
Barge
Catamaran

ABSTRACT

Whilst floating photovoltaic (FPV) is gaining attention for ocean-based applications, their motion response in waves significantly affects structural integrity and power generation efficiency. In particular, FPV is expected to operate in arrays consisting of extensive solar panels, and thus, floating solar systems are required to be analysed with neighbouring devices connected by joints. This study investigates the seakeeping characteristics of two FPV systems in arrays, comparing conventional barge floats with twin-hull (catamaran) floats under various wave conditions. A systematic investigation using Computational Fluid Dynamics (CFD) was conducted for the hydrodynamic response of both isolated-single-floater and multi-body (1×3) configurations in regular waves, with non-dimensional wavelength ratio (λ/L) 1.62–4.27 to the floater length. Wave tank experiments were conducted to validate the CFD model, showing agreement with less than 10% discrepancies. The study focused on the multi-body behavior of heave and pitch Response Amplitude Operators (RAOs) and mooring line forces. Results show that the multi-catamaran configuration exhibited lower heave RAOs (by approximately 20%) compared to multi-barge pontoons in long waves ($\lambda/L > 2.47$) while maintaining similar pitch responses. However, in shorter waves ($\lambda/L < 2$), the catamaran configuration showed up to 15% higher RAOs than barge's. The multi-body arrangement demonstrated significant array effects, with the leading float experiencing 30% higher mooring loads than the trailing float. The leading float also experiences the highest mooring forces. As the wavelength ratio increases, the barge float's front mooring force increases dramatically, reaching nearly twice that of the catamaran at a ratio of 4.27. These findings align with the RAO results, indicating that the barge float is more wave-sensitive under long-wavelength conditions, whereas the catamaran demonstrates superior station-keeping with lower mooring forces. This work provides quantitative guidance for selecting appropriate floater forms for FPV applications based on expected wave conditions.

1. Introduction

1.1. Background of the floating solar system

The increasing global demand for energy and the urgent need to combat climate change have made developing renewable energy sources a critical strategy for mitigating environmental impacts. Floating Photovoltaic (FPV) technology is increasingly regarded as an effective solution to the challenges of energy supply and land resource limitations as an emerging green innovation. FPV involves the installation of solar panels on the surface of water bodies, such as reservoirs, lakes, and even oceans, serving as an alternative to traditional land-based photovoltaic

systems. Compared to terrestrial solar installations, FPV offers significant advantages, including the conservation of land, reduced environmental impact on the landscape, and enhanced solar panel efficiency through the natural cooling effect of water bodies (Cazzaniga et al., 2018). This cooling effect not only improves the power generation efficiency of the solar panels but also extends the system's operational lifespan. Furthermore, FPV can effectively reduce water evaporation, which is particularly beneficial for water resource management in arid and semi-arid regions. These benefits give FPV systems substantial technical and economic potential for widespread development (Haas et al., 2020), (Jacobson and Delucchi, 2011).

The FPV sector has experienced significant growth in recent years.

* Corresponding author.

** Corresponding author. Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, MK43 0AL, United Kingdom.

E-mail addresses: jaehoon.seo@inha.ac.kr (B.C. Cerik), Luofeng.huang@cranfield.ac.uk (L. Huang).

<https://doi.org/10.1016/j.oceaneng.2025.120970>

Received 6 January 2025; Received in revised form 25 February 2025; Accepted 12 March 2025

Available online 13 March 2025

0029-8018/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Many countries have implemented FPV projects on reservoirs and lakes to meet their increasing electricity demands and fulfil environmental policy goals. The first FPV systems emerged in 2007, initially applied in Japan and France. Since then, advancements in technology and reduced installation costs have facilitated the rapid expansion of FPV capacity. Today, numerous countries and regions worldwide are actively promoting FPV technology development, with Southeast Asia and Europe leading the way in adoption (Maghami et al., 2016), (Rosa-Clot and Tina, 2017). The design of FPV systems typically involves the integration of multiple technologies, including the coordination of float structures, anchoring systems, photovoltaic modules, and electrical systems. The floating structure serves as a platform to support the photovoltaic components and must withstand complex environmental conditions such as waves, wind, and tides (Sahu et al., 2016). Therefore, optimising the design and structural layout of the float to enhance system dynamic response and energy output remains one of the critical research challenges in the FPV field. Fig. 1 presents the main classifications of FPV systems currently available (Claus and López, 2022).

Floating solar installations can be categorised into three main float configurations and two specialised designs. High-density polyethylene (HDPE) is commonly used for float construction, while steel and aluminium are typically employed in supporting structures. The first configuration uses cylindrical floats, representing the earliest FPV designs. While these offer simple deployment and lower costs, their application is limited to wave heights below 2 m. The second configuration employs modular floats, where individual PV panels are supported by separate float units. These modular systems incorporate maintenance walkways and housing for electrical components and can be adapted for various panel sizes and inclination angles, though at a

higher cost than cylindrical floats. The third configuration consists of integrated platform arrays, where multiple floats are connected to form a continuous surface for PV panel installation. While this arrangement facilitates maintenance access, it requires a higher initial investment (Claus and López, 2022).

Two additional concepts have emerged for offshore applications. The first is a submersible system capable of operating at depths up to 2 m, using ballast control for depth adjustment. However, its motion response characteristics in offshore conditions remain to be validated. The second is a flexible system utilising deformable modules or foam elements instead of rigid floats. This design aims to reduce structural complexity and accommodate wave motions through compliance rather than resistance, though its performance characteristics in various sea states require further investigation.

1.2. Development of ocean-based floating solar systems

The application of FPV systems initially focused on calm water environments, such as inland reservoirs and lakes, where the low turbulence levels meant that hull form requirements were relatively straightforward. However, with advances in technology and increasing demand for renewable energy, researchers have gradually begun to explore the potential for FPV deployment in open water and marine environments (Spencer et al., 2019). Compared to calm water settings, the wave and wind conditions in marine environments are far more complex, imposing higher demands on the design of floating structures. In these challenging conditions, the floats must not only maintain the motion response of the photovoltaic modules but also withstand the effects of wave-induced motions and tidal variations. Existing studies

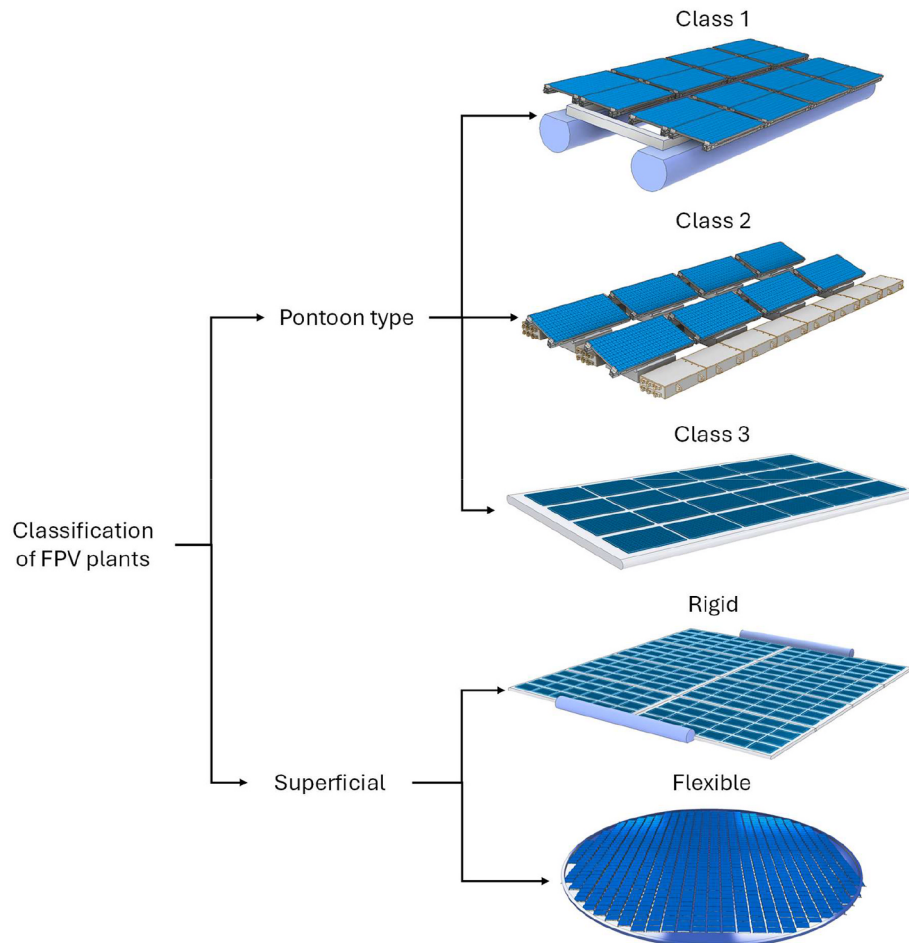


Fig. 1. Classification of FPV systems (Huang et al., 2025).

indicate that traditional square or barge float-shaped floats are prone to significant heave and pitch motions under high wave conditions, adversely impacting the power generation efficiency and structural safety of the photovoltaic system (Trapani and Millar, 2013), (Trapani and Redón Santafé, 2015). A new FPV design that is better suited for ocean environments is essential, such as the flexible FPV system depicted in Fig. 1. Its circular structure is particularly advantageous for deep-sea applications, as it is designed to withstand incoming waves from all directions. Starting with a basic floating body for design optimisation, rather than a fully complex structure, offers a more efficient and direct approach to enhancing motion response and performance in challenging marine environments. As a result, developing innovative hull forms that can adapt to complex wave conditions has become a key direction in the advancement of FPV technology.

Despite the evident advantages of floating photovoltaic systems, their deployment in open sea environments still faces numerous challenges. For example, wave-induced motion can cause tilting and positional shifts of the photovoltaic modules, reducing the system's overall efficiency. Additionally, strong waves may impose extra loads on the mooring systems, increasing the risk of structural damage. Consequently, one primary research focuses on achieving a balance between flexibility and motion response in the hull form to accommodate various complex water conditions (Sahu et al., 2016). Fig. 2 illustrates two pontoon-type structures, cylinder and modular. Fig. 2 (a) shows a cylindrical structure featuring photovoltaic panels mounted on two rollers. It can effectively reduce adverse motions in waves and enhance the performance and motion response of FPV systems in harsh marine environments, but it can operate under a certain maximum wave height (Spencer et al., 2019), (Trapani and Redón Santafé, 2015). Fig. 2 (b) shows barge float-shaped floats; it has a better seakeeping response than a cylinder structure but at a higher cost. The cylindrical hull form shown in Fig. 2 (a) employs a longitudinal arrangement where the cylinder's axis is parallel to the incident wave direction. While this simple geometry has been widely used in early FPV systems, its motion response characteristics in waves are limited by its basic form. A more hydrodynamically efficient design can be achieved by combining the wave-piercing characteristics of a pointed bow with the modularity of barge pontoons. This naturally leads to a catamaran configuration, where twin hulls with streamlined forward sections can provide improved wave interaction characteristics while maintaining the practical advantages of modular construction. Recent studies suggest that such hull form optimisation, particularly the adoption of catamaran configurations, could significantly enhance the seakeeping performance of pontoon-type FPV systems. The twin-hull configuration offers potential advantages in terms of reduced heave and pitch motions in waves while providing a stable platform for solar panel installation (Claus and López, 2022).

1.3. Application of CFD in FPV research

Computational Fluid Dynamics (CFD), as a numerical simulation technique, has been widely employed to investigate the hydrodynamic

behaviour of floating structures under various wave conditions. CFD simulations enable precise analysis of the six degrees of freedom motion of floats (including heave, pitch, and roll) and facilitate exploration of the interactions between the floating body and the surrounding fluid (van der Zanden et al., 2024). Compared to traditional physical experiments, CFD simulations reduce research costs and allow for the rapid generation of extensive data within a shorter time frame. As a result, CFD has become a crucial tool for studying the hydrodynamic characteristics of FPV systems, optimising hull form, and improving the power generation efficiency of photovoltaic systems (Ghigo et al., 2022), (Mekonnen et al., 2023). In previous research, many scholars have used CFD simulations to investigate the wave response of various float shapes, revealing the significant impact of hull form on wave loading patterns and motion characteristics. For example (Song et al., 2023), uses numerical models to analyse the hydrodynamic characteristics of floating photovoltaic (FPV) systems in marine environments, particularly under the combined action of wind, waves, and ocean currents. The response characteristics of a single-row floating photovoltaic system and the influence of wave parameters such as wavelength and wave height on the dynamic response of the system are investigated.

Despite the widespread application of CFD in the FPV field, most research has focused on traditional square or barge hull forms. While these studies provide valuable theoretical support for the deployment of FPV systems in calm water environments, their applicability in complex marine conditions remains limited (Al-Yacoubi et al., 2020). Twin-hull float configurations have been investigated as an alternative to conventional barge floats to improve motion response characteristics in waves. While catamaran hull forms are well-established in marine vessels for their wave interaction characteristics, their application to FPV systems presents unique challenges and opportunities. The twin-hull configuration can modify wave diffraction and radiation patterns around the platform, potentially leading to different motion responses compared to single-hull floats. These hydrodynamic characteristics may be particularly relevant for FPV systems operating in moderate wave environments where motion reduction is critical for operational efficiency (Ramana et al., 2024).

In FPV systems analysis, CFD methods are applied to study both single-float and multi-float configurations. Multi-float arrangements are particularly important as they represent actual FPV installations where multiple units are connected. The hydrodynamic behaviour of such arrays is complex, involving wave diffraction and radiation effects between the floats. The spacing between floats influences these wave interaction effects and consequently affects the motion responses and loads experienced by each float. Wave forces on floats within an array can differ significantly from those on isolated floats due to sheltering effects and wave field modifications. Understanding these interaction effects is crucial as commercial FPV installations typically consist of large arrays of interconnected floating units.

1.4. Innovative design of catamaran floats

The catamaran structure is a classic ship design known for its

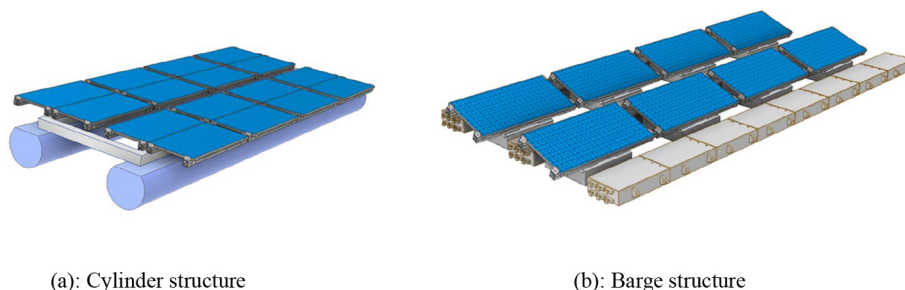


Fig. 2. Two pontoon-type FPV systems.

reduced motion response and seakeeping capabilities. The catamaran float structure consists of two parallel hulls, which excel at reducing heave, pitch, and roll motions (Magkouris et al., 2021). The twin-hull configuration modifies wave diffraction patterns and can create wave interaction effects between the hulls. These hydrodynamic interactions influence the motion response characteristics of the float. In FPV applications, the motion characteristics, particularly pitch and heave responses, affect the orientation of solar panels relative to optimal sun angles. The relationship between hull form and motion response, therefore, has implications for power generation, though this depends significantly on the specific wave conditions and float dimensions (Cutler et al., 2022).

Moreover, the introduction of catamaran structures provides additional design possibilities for floating bodies. For instance, multiple rows of photovoltaic modules can be arranged on the central platform of the catamaran float, while the two hulls on either side can enhance the system's buoyancy and motion response. This multifunctional design not only helps to optimise the system layout but also increases the total power output by accommodating more photovoltaic modules. Additionally, the modular nature of the catamaran float structure offers greater flexibility in installation and maintenance, which can help reduce construction and operational costs (Magkouris et al., 2021).

1.5. Scope and novelty of this paper

This study investigates the application of twin-hull float configurations for Floating Solar Photovoltaic (FPV) systems through systematic numerical analysis. While twin-hull designs are common in marine vessels, their hydrodynamic characteristics in FPV applications have not been thoroughly investigated. The study compares motion responses of twin-hull and barge float configurations in regular waves, focusing on both single-float and multi-float (1×3) arrangements.

Most existing FPV systems employ barge floats and are typically deployed in sheltered waters. Previous studies have characterised the motion responses of such configurations, showing significant heave and pitch motions in waves that can affect solar panel orientation (Zheng et al., 2024). The present work extends this understanding by examining how twin-hull configurations might modify these motion characteristics through wave diffraction and interference effects.

The key contributions of this study include.

- Development and validation of CFD models against wave tank measurements for both single and multi-float configurations
- Systematic comparison of motion Response Amplitude Operators (RAOs) between twin-hull and barge float configurations across a range of wave conditions
- Analysis of hydrodynamic interactions in a three-float array, including investigation of sheltering effects and motion response variations between leading and trailing floats
- Quantification of mooring load distributions in multi-float arrangements

The results provide quantitative guidance for float configuration selection based on expected wave conditions and inform spacing considerations for multi-float arrays. This work aims to extend the application envelope of FPV systems beyond sheltered waters through an improved understanding of hydrodynamics.

2. Computational approach

2.1. Computational domain and boundary conditions

To computationally reproduce the response of the floating body and the water flow process, a three-dimensional domain was created in STAR-CCM+. This computational domain was filled with water to a depth (D) in the lower part, while the upper part was filled with air. It

has a length (L), width (W), and water depth (D), which are the exact same dimensions compared to the experimental wave tank at Cranfield University. The computational domain was created by STAR-CCM+ and is shown in Fig. 3.

The floating body was initialised at water depth (D) and with a specific mooring angle (θ). The x-axis is parallel to the wave's coming direction, and the y-axis is positive upwards. Gravity is negative downwards, and the wave direction is **negative x** direction. The domain setting is shown in Fig. 3 (c). Three floating bodies were placed in the middle of the domain; the wave generation and absorption zone have 2 wavelength(λ) lengths. The middle floating body was placed in the middle of the domain to ensure the wave generation zone had enough length during each wavelength ratio. The front and rear floating bodies were moored to the bottom of the domain with 45° to the x-axis.

The main parameters of the computational domain are given in Table 1.

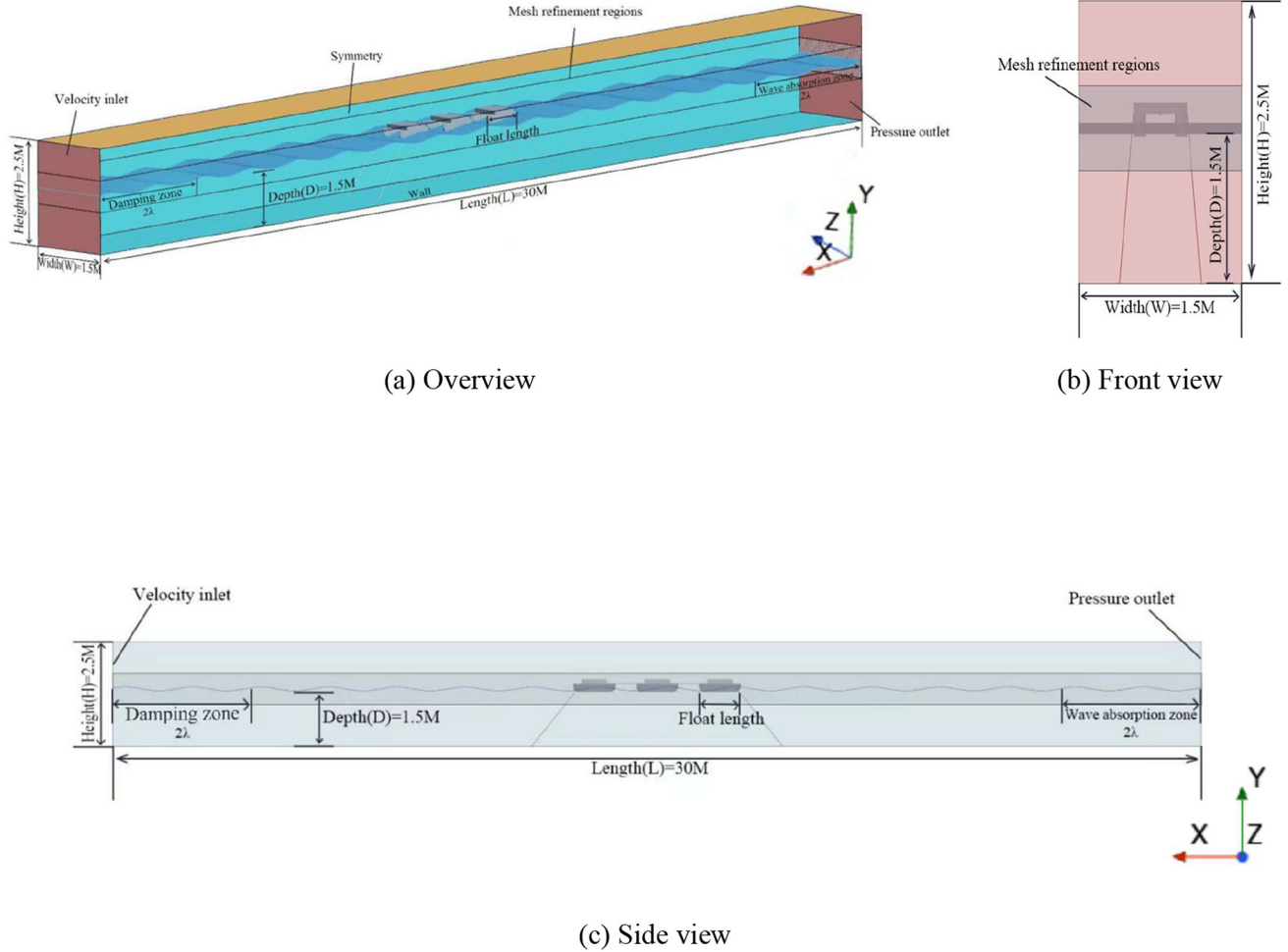
A velocity inlet boundary condition was applied at the front boundary of the domain, while the back boundary was set as a pressure outlet. The bottom boundary was modelled as a wall to represent the base of the wave tank. The top boundary was designated as a pressure outlet to simulate atmospheric conditions. The region surrounding the floats is designated as mesh refinement zones. The two vertical side boundaries were defined as walls to accurately reproduce the experimental wave tank environment within the computational domain.

Following the implementation of the damping zone, as illustrated in Fig. 3, wave generation tests were conducted in an empty domain without FPV structures to validate the efficacy of the 2λ -length damping zone in mitigating reflected waves at the inlet. This ensures that subsequent waves entering the domain conform to the prescribed wave height and wavelength. Two wave gauges were positioned at 2λ and 4λ from the inlet to monitor wave amplitude under 10 cm wave height. As depicted in Fig. 4 (a), the wave height within the damping zone near the inlet exhibits a marked reduction due to the energy absorption mechanism. Fig. 4 (b) further demonstrates that wave gauges at 2λ and 4λ show nearly identical wave heights, confirming minimal disturbance to wave propagation beyond the damping region. These results verify the rationality of the 2λ damping zone length. Even for the maximum wavelength of 4.27 m, where the damping zone spans 8.54 m, the configuration remains effective, as the floating structure is positioned at the tank centre, which is 15 m, ensuring sufficient isolation from boundary reflections.

2.2. Floating structures and mooring system

Two float configurations were investigated in this study: a twin-hull (catamaran) and a barge float, both designed to support a commercial standard solar panel (Model T050M365, TDG Holding Co. Ltd). The three-dimensional geometry of both configurations is shown in Fig. 5 (a), with principal dimensions provided in Table 2. The dimensions of two floating structures were designed to be as close as possible to fit the same commercial solar panel.

The draught of the floating bodies was adjusted in response to the applied mooring forces. The parameters for the domain system are detailed in Table 1. The total draught consists of the static equilibrium draught and additional sinkage due to mooring pretension. The draught of the floating body is influenced by its weight, displacement, shape, water density, and loading conditions. Two floating bodies' mass is provided in Table 2, and the support structure weighs 11.53 kg. The draught calculations for the catamaran and the barge float must be conducted separately due to the differences in the shapes and weights of their floats. These variations can significantly affect how each type of float interacts with the water, including how deeply each submerges. Accurate draught calculation is crucial for predicting motion response, buoyancy, and overall performance in the water, making it essential to consider the unique characteristics of each float type during simulation and design processes. Both floating bodies were anchored to the bottom



(a) Overview

(b) Front view

(c) Side view

Fig. 3. Computational domain of wave tank in STAR-CCM+.

Table 1

Main parameter of the computational domain.

Parameters	Magnitude
Length (m)	30
Width (m)	1.5
Height (m)	2.5
Water depth (m)	1.5
Float length (m)	1
Domain size ratio	30
Water depth to float length ratio	1.5
Wave generation zone length	2
Wave absorption zone length	2

of the wave tank using four identical mooring lines made of fishing lines with a diameter of 0.18 mm. Spring connections at the line-floater interfaces provided a pretension force of 20 N for structural stabilisation. The mooring system configuration and mechanical parameters are detailed in Table 3, including the angle relative to the wave tank, spring stiffness, and component lengths. The mooring lines were modelled as equivalent spring systems in the numerical simulations, with each line-spring assembly simplified to a single spring element. The spring properties, including stiffness and pretension, were uniformly applied to represent the combined behaviour of the fishing line and spring connection.

The calculation of the draught of a floating body only needs to use the buoyancy calculation formula

$$Mg = \rho(Ah)g \quad (1)$$

In the equation, M represents the mass of the floating body, the fluid density is denoted by ρ , and A represents the waterplane area of the floating body. The floating body's draught is represented by h . The main parameters of the two floating bodies are shown in Table 2.

Based on the data from Table 2, the static draughts of the two floater configurations were 2.3 cm for the barge and 4.6 cm for the catamaran. Using mooring parameters from Table 3, the additional draught induced by the pretensioned mooring lines was given. Each float is connected to the seabed by four mooring lines at 45° , with a pretension force of 20 N per line. The vertical component of the total mooring force was calculated as 56 N. Due to the distinct waterplane areas of the two float types, this vertical force results in an additional draught of 0.854 cm for the barge and 2.0 cm for the catamaran. Consequently, the total operational draughts are 3.154 cm for the barge and 6.6 cm for the catamaran.

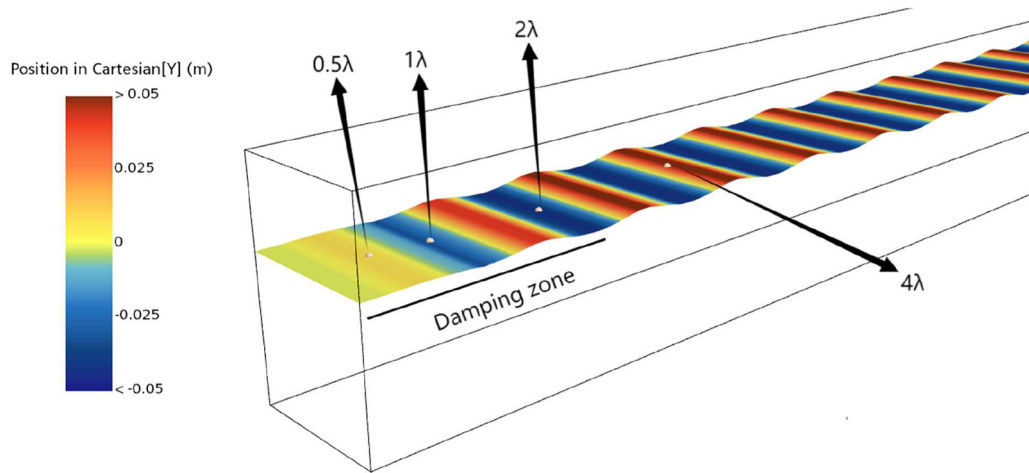
2.3. Physical model and wave condition

The simulations for this investigation were performed using STAR-CCM+ 23.02, employing the $k-\omega$ Shear Stress Transport (SST) turbulence model (Menter, 1993).

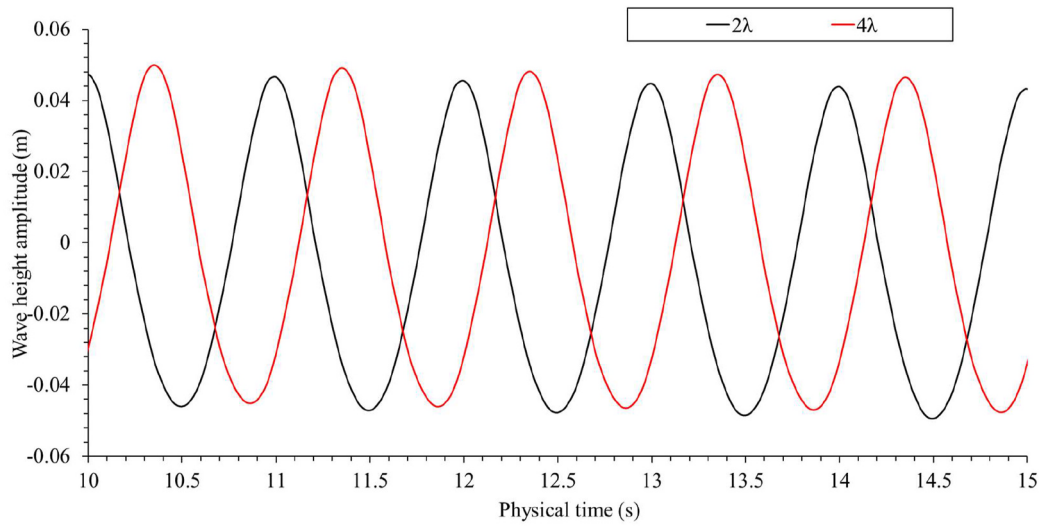
The solution for the fluid domain was achieved by solving the Reynolds-averaged Navier-Stokes (RANS) equations, which describe the behaviour of an incompressible Newtonian fluid:

$$\nabla \cdot \bar{\mathbf{V}} = 0 \quad (2)$$

$$\frac{\partial(\rho \bar{\mathbf{V}})}{\partial t} + \nabla \cdot (\rho \bar{\mathbf{V}} \bar{\mathbf{V}}) = -\nabla \bar{P} + \nabla \cdot \rho(\bar{\boldsymbol{\tau}} - \rho \bar{\mathbf{v}} \bar{\mathbf{v}}) + \rho \mathbf{g} \quad (3)$$



(a): Computational domain without FPV structures



(b): Comparison between 4 wave gauges under 10 cm wave height

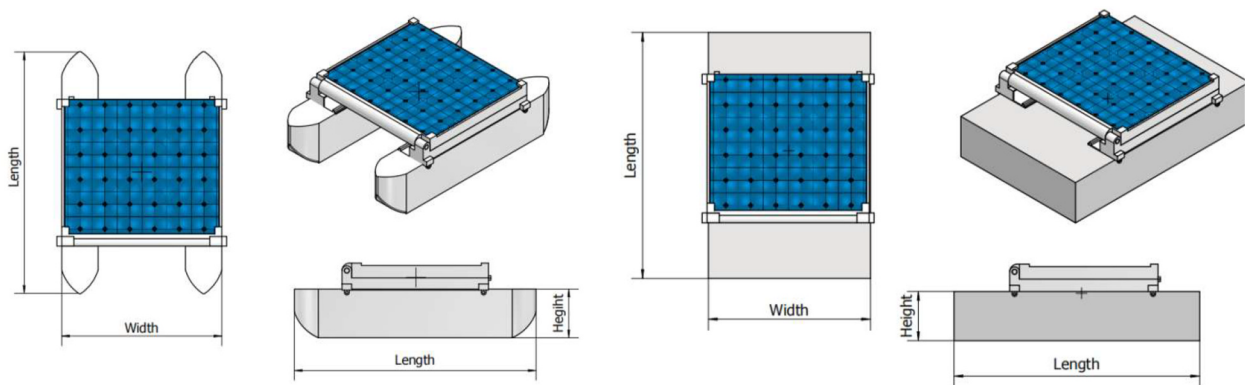
Fig. 4. Damping zone length validation.**Fig. 5.** 3D view of catamaran and barge floats.

Table 2

The main parameters of two floating bodies.

	Catamaran float	Barge float
Length (m)	1	1
Width (m)	0.66	0.66
Draught (m)	0.066	0.032
Mass (kg)	12.9	15.2
Vertical centre of gravity, VCG (m)	0.236	0.138
Mass moments of inertia (kg-m ²)		
I_{xx}	0.568	0.573
I_{yy}	0.965	1.401
I_{zz}	0.482	1.018

Table 3

Main parameters of the mooring system.

	Fishline	Spring
Length (m)	1.9	0.2
Angle with wave tank (degree)	45	45
Pre-tension force (N)	/	20
Spring stiffness (N/m)	/	454.54
Averaged mass per unit length (kg/m)	0.005	
Minimum breaking load (kg)	23.3	/

In these equations, $\bar{v}$ represents the time-averaged velocity vector, while $\bar{v}'$ is the fluctuating component. The fluid density is denoted by ρ , and p represents the time-averaged pressure. The viscous stress term is $\tau = \mu[\nabla v + (\nabla v)^T]$, where μ is the dynamic viscosity. The gravitational acceleration is set at 9.81 m/s². Since the RANS equations account for turbulent effects, a turbulence model is required to close the equations. The Shear Stress Transport (SST) $k-\omega$ model (Menter, 1993) was employed in this study. The SST $k-\omega$ model is recognised as a robust approach for RANS turbulence modelling, mainly due to its effectiveness in capturing the flow characteristics along boat hulls (Paterson et al., 2003).

A multiphase-flow model, including air and water, was applied to the computational domain. The Volume of Fluid (VOF) method (Hirt and Nichols, 1981) is a technique used in computer simulations to track and model the surface between two fluids, such as air and water. It divides the simulation area into a grid and assigns each cell a value indicating how much water it contains.

The VOF method employs a passive scalar, α , which represents the fractional volume of a cell occupied by a specific phase. In this context, a value of $\alpha = 1$ corresponds to a cell completely filled with water, while $\alpha = 0$ indicates a cell filled entirely with air. The free surface, which is a mixture of these two phases, is formed by cells where $0 < \alpha < 1$. The elevation of the free surface over time is determined by the advection equation for α , expressed in Equation (4). Cells containing both air and water's density and viscosity are calculated using linear interpolation, as described in Equation (5) and Equation (6).

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\bar{v} \alpha) = 0 \quad (4)$$

$$\rho = \alpha \rho_{\text{water}} + (1 - \alpha) \rho_{\text{air}} \quad (5)$$

$$\mu = \alpha \mu_{\text{water}} + (1 - \alpha) \mu_{\text{air}} \quad (6)$$

In this study, $\rho_{\text{water}} = 1000 \text{ kg/m}^3$, $\mu_{\text{water}} = 8.90 \times 10^{-4} \text{ N s/m}^2$; $\rho_{\text{air}} = 1 \text{ kg/m}^3$, $\mu_{\text{air}} = 1.48 \times 10^{-5} \text{ N s/m}^2$.

By updating these values as the fluids move, the VOF method accurately tracks the interface between them. This is particularly useful for simulating waves, as it can create and follow the movement of waves, showing how they interact with structures like ships or coastal barriers. Gravitational acceleration was set to 9.81 m/s², acting downward along the y-axis.

The waves were modelled using a fifth-order VOF wave method to test the performance of floating bodies. Both floating bodies were tested

Table 4

Main parameters of different wave conditions under 1.5m water depth.

Case	Wavelength λ (m)	Wavelength to float length ratio (λ/L)	Wave number k (rad/m)	Wave height H_1 (m)	Wave height H_2 (m)
1	1.62	1.62	3.88	0.05	0.1
2	1.94	1.94	3.24	0.05	0.1
3	2.47	2.47	2.54	0.05	0.1
4	3.21	3.21	1.96	0.05	0.1
5	4.27	4.27	1.47	0.05	0.1

Table 5

Wave environment parameters.

Wave frequency (Hz)	Wavelength λ (m)	Δx 1/80 (m)	Δx 1/100 (m)	Δz 1/20 (m)
0.6	4.27	0.053	0.043	0.005
0.7	3.21	0.040	0.032	0.005
0.8	2.47	0.031	0.025	0.005
0.9	1.94	0.024	0.019	0.005
1	1.62	0.020	0.016	0.005

under various wave conditions while maintaining the same water depth. The main parameters for these wave conditions are provided in Table 4.

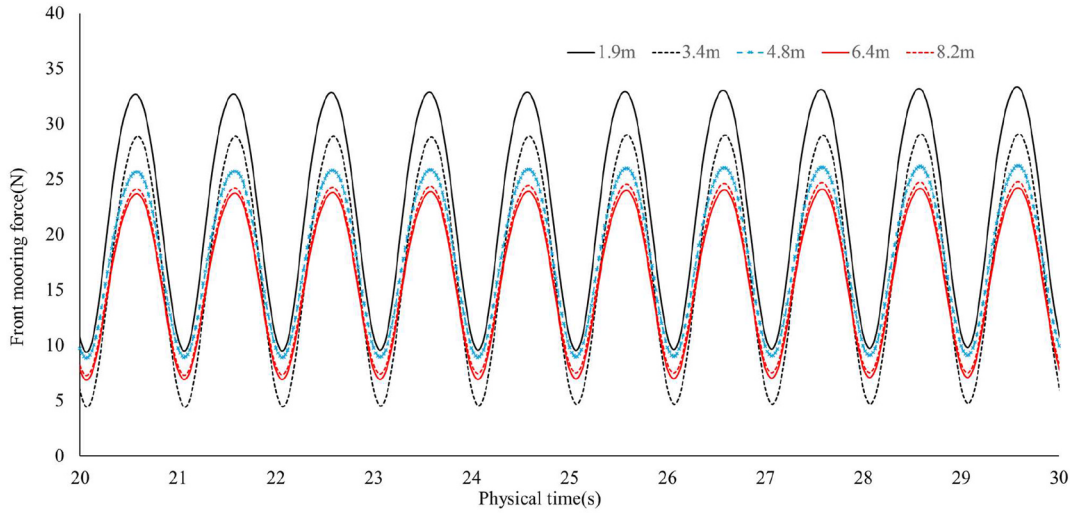
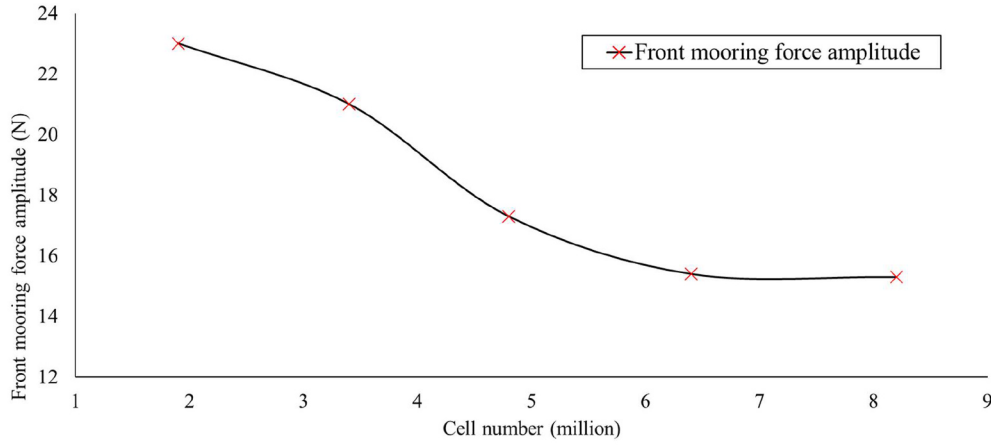
2.4. Mesh sensitivity and overset mesh

A mesh sensitivity study, also known as a mesh convergence study, is essential in computational fluid dynamics (CFD) to ensure that simulation results are independent of the mesh size or resolution (see Table 5). This process involves creating several meshes with varying levels of refinement, running the same simulation on each, and comparing the results. One can determine if the results stabilise and show slight variation with finer meshes by analysing the differences in crucial output parameters such as pressure, velocity, and forces across different mesh sizes. This indicates that the solution is mesh-independent or converged. The goal is to identify an optimal mesh size that balances accuracy and computational efficiency.

As the computational cost increases with the cell number, a mesh sensitivity study was conducted to get a reliable solution with as few cells as possible. The computational domain was discretised using the Finite Volume Method to solve the governing equations (Versteeg and Malalasekera, 2007). The meshing approach is illustrated in Fig. 6. The cells are primarily cubic, although their shape may vary in certain regions, such as around the curvature of the floating bodies. The domain was discretised using a base size ($d = \Delta x = \Delta y = \Delta z = 0.1 \text{ m}$). Unique mesh treatments were applied in this case: (a) The fluid region outside the floating body and the wave interaction region are refined; (b) The area between the tank and the floating body near the free surface; (c) overset the fluid domain outside the floating body and the wave interaction area of the tank.

The refined region mesh division needs to be based on different simulation cases. x is the direction of the wave, Δx is the 1/80–1/100 of wavelength λ . y is the width of the wave tank, which is constant at 1.5 m, $\Delta y = 0.1 \text{ m}$, which is the base size of the mesh. z is the direction of wave height, Δz is 1/20–1/40 of wave height h . The base size d of the domain is 0.5 m, and the wavelength depends on each case frequency. In the mesh sensitivity test, the evaluation began with the theoretical minimum mesh size (Wang et al., 2022). When the wavelength was 1.62 m, the corresponding mesh spacing $dx = 0.0162$. The wavelength was gradually increased during the mesh sensitivity test until it reached a maximum value of 4.27 m, and $\Delta x = 1/80 \times 4.27 = 0.053 \text{ m}$.

Given that the wave heights are only 5 cm and 10 cm, using a mesh size of 1/40 of the wave height would result in a tiny mesh size of 0.00125 m. This would make the simulation unfeasible due to the tiny grid size. Therefore, for all wave height cases, a mesh size of 1/20 of the

(a): Front mooring force of barge float comparison between different cell numbers ($h=10$ cm)(b): Front mooring force amplitude of barge float as the function of cell number($h=10$ cm)**Fig. 6.** Front mooring force of barge float mesh sensitivity test.

10 cm wave height, which is 0.005 m, was chosen for the grid size in the z -direction (Song et al., 2024).

Considering that redividing the grid according to the wavelength of each case would result in a significant waste of resources, Table 4 shows the Δx values at different frequencies and wavelengths. The table shows that the largest Δx is 0.053, and the smallest is 0.016. The Δx values fall within this range. By conducting grid sensitivity tests specifically for the cases with the minimum wavelengths and identifying where the results begin to converge, resources can be considerably conserved, and computation speed can be significantly improved.

Given that most of the data are close to integer values, the Δx values chosen for the mesh sensitivity tests are $\Delta x_1 = 0.016$ m, $\Delta x_2 = 0.02$ m, $\Delta x_3 = 0.03$ m, $\Delta x_4 = 0.04$ m, and $\Delta x_5 = 0.05$ m. The Δz was kept the same as 0.005 m for all cases. The five sets of mesh were tested under wavelength 1.62 m with the same wave height $h = 10$ cm and water depth $D = 1.5$ m; a barge float floating body was used as the template floating body. Table 6 shows the total mesh numbers under different

sizes of Δx .

According to theoretical guidelines, the mesh size for simulating a wavelength of 1.62 m should ideally be between 1/80 and 1/100 of the wavelength. However, the mesh size should not exceed 0.053 m in all cases, corresponding to 1/80 of the maximum wavelength of 4.27 m considered in the simulations and demonstrating that using the largest permissible mesh size for the smallest wavelength also yields convergent results and can significantly reduce computational time. Suppose it's established that this maximum mesh size still maintains accurate and stable results across smaller wavelengths. In that case, it allows for a more efficient simulation process, optimising computational resources without compromising the quality of the results.

The size of each time step was determined by a prescribed Courant number (C_0) value, according to the expression:

$$C_0 = \frac{V_n \Delta t}{\Delta x} \quad (7)$$

In this context, Δt represents the time step size, V_n denotes the flux speed through the shared face between two neighbouring cells, and Δx is the distance between the centres of these two cells. The Courant number (C_0) is constrained to be less than 1, a standard in ship hydrodynamic CFD simulations. Time step size is automatically adjusted according to the size of the cells being tested, ensuring motion response and accuracy in the simulation results (Ferziger et al., 2019).

Table 6
Mesh parameters.

Δx (m)	0.016	0.02	0.03	0.04	0.05
Δz (m)	0.005	0.005	0.005	0.005	0.005
Total mesh number(million)	8.2	6.4	4.8	3.4	1.9

Fig. 6(a) compares the front mooring force across different cell numbers, revealing that as the cell number increases, the peak and trough values of the mooring force decrease, leading to a reduction in amplitude. This trend indicates improved simulation precision with finer meshes. Specifically, when the cell number reaches 4.8 million, which is the blue dashed line in Fig. 6(a), the peak and trough values closely align with those of the 6.4 million-cell case. Furthermore, the comparison between 6.4 million and 8.2 million cells shows nearly overlapping curves, suggesting negligible accuracy gains beyond 6.4 million cells. Fig. 6(b) demonstrates that the front mooring force converges as the number of cells increases. The difference in results between 6.4 million and 8.2 million cells is negligible, indicating that using more than 6.4 million cells or reducing the mesh size below $\Delta x = 0.02$ m would not yield significant improvements in accuracy. This mesh resolution provides an optimal balance between computational efficiency and solution accuracy.

An overset mesh, also known as a chimera mesh, is a method used in computational fluid dynamics (CFD) to handle complex and dynamic geometries, particularly useful when simulating scenarios involving moving objects within a fluid domain. This technique involves layering multiple meshes, where a base mesh covers the entire computational domain, and additional detailed meshes focus on specific areas or objects. These detailed meshes can move and rotate independently, allowing for precise simulations of interactions and movements such as aircraft dynamics or ship manoeuvres (Chen et al., 2023).

Setting up an overset mesh in STAR-CCM+ involves adhering to specific conditions to ensure optimal functionality and accuracy

(Schreck et al.). Firstly, the configuration requires at least two distinct mesh layers to accommodate varying levels of detail and interaction. Secondly, the largest mesh size must be at least three times the size of the smallest mesh currently implemented, allowing for a broad coverage with adequate resolution where needed. Lastly, the mesh size of any moving object and its immediately surrounding fluid layer must be similar to ensure seamless data transition and accurate simulation of fluid dynamics around the moving object (Benites-Munoz et al., 2020).

Fig. 7 shows three different layers of mesh of multi-catamaran. In setting up the overset mesh for a water tank simulation in STAR-CCM+, three distinct mesh layers are utilised to optimise the balance between computational efficiency and accuracy ("Introductory Guide to Overset Simulations"). The first mesh layer covers most of the water tank, primarily the upper and lower sections, relatively distant from the free liquid level. This layer has a coarser grid size of 0.1 m to conserve computational resources and time. The second layer, located near the free liquid surface, is more refined with a mesh size of 0.02 m; this size was validated through a prior grid sensitivity test, ensuring it captures the dynamics at the liquid surface accurately. The third mesh layer surrounds the entire floating body, representing the outflow field of the body. The second and third layers are interconnected into an overset mesh configuration, with similar mesh sizes of 0.02 m in the incident wave direction and 0.005 m in the wave height direction, as tested and found suitable in previous grid sensitivity analyses. Fig. 7 illustrates the overset mesh arrangement between the catamaran floating body and the wave tank. Fig. 8 shows the image demonstrating that the outflow field of the floating body after the overset mesh internalisation settings are

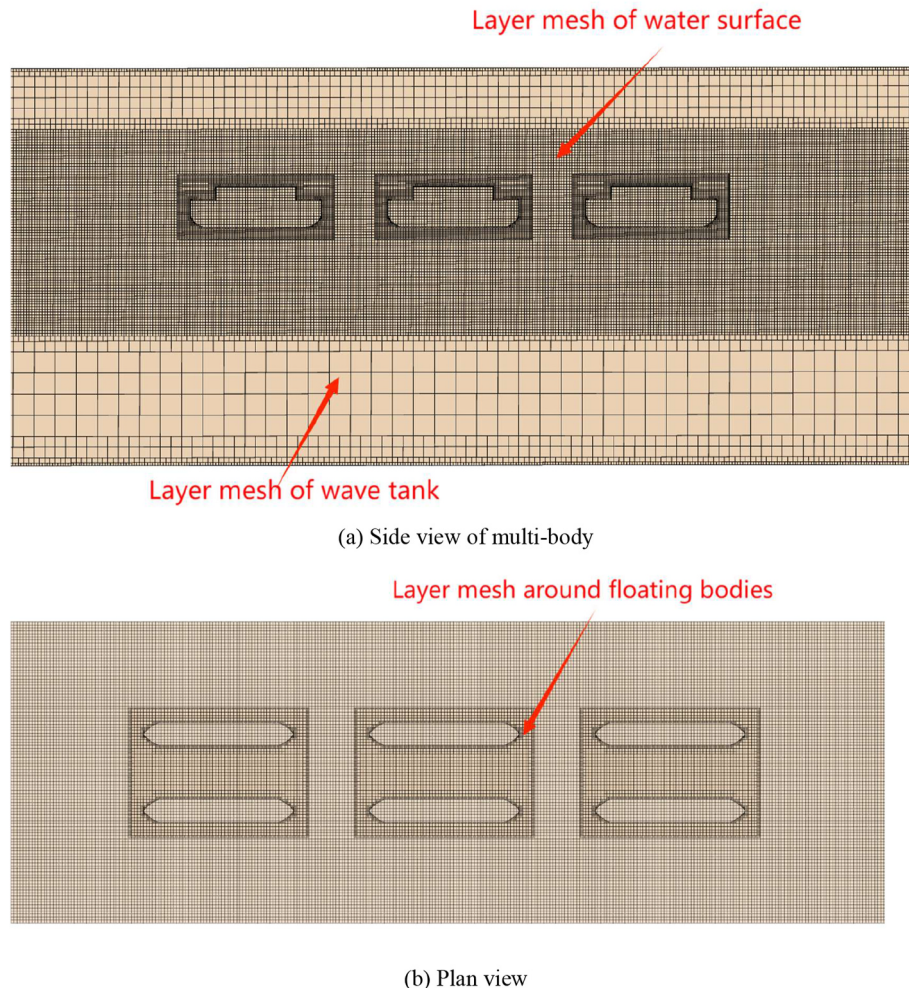


Fig. 7. Mesh layout of the model.

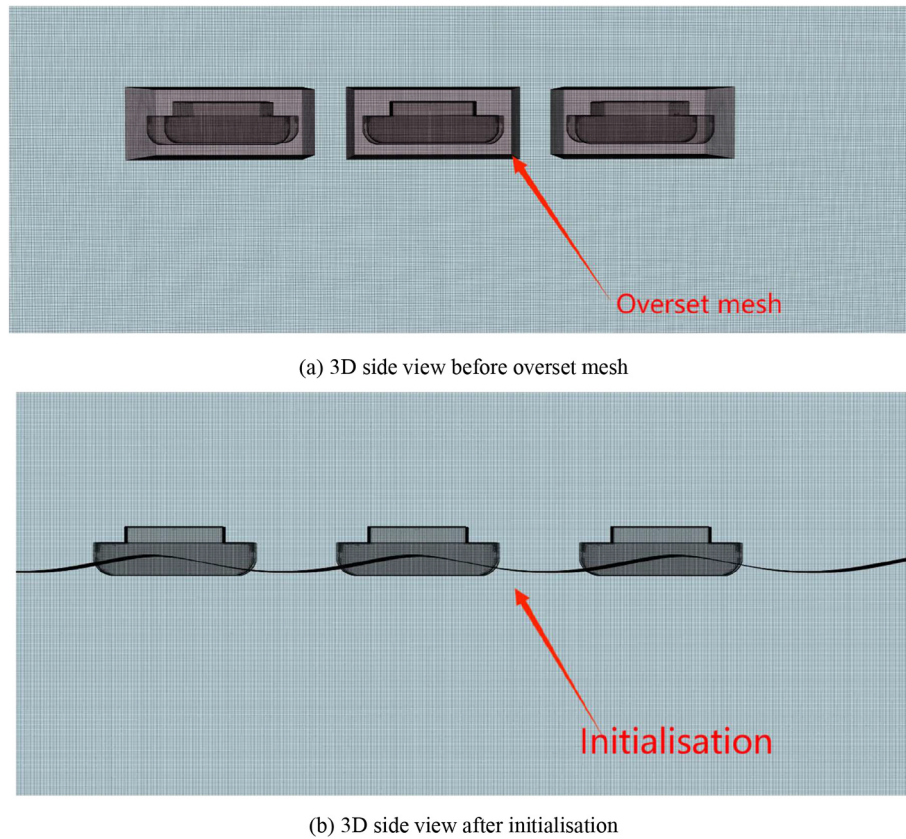


Fig. 8. Illustration of overset mesh used.

implemented.

2.5. Data processing

Before simulating the multi-body structure, the single float should be simulated to prove the reliability of the simulation. As depicted in Fig. 9, the floating body rises with the wave's crest and descends, following the wave's contour. The mooring system provides an appropriate tension throughout the periodic wave-induced motions, ensuring the floating body's position remains relatively stable in the wave momentum. Notably, when the wave's crest impacts the floating body, the forward anchoring chain bears increased tension, and the backward anchoring chain bears less tension than a forward anchoring chain.

Fig. 9(a) and (b) display the response of the catamaran and barge float under various floating surfaces during wave crest impact. It is visible that under the same wave conditions, the catamaran's bow exhibits noticeable warping, whereas the barge float does not. Fig. 9 (c) and (d) depict the interaction between the wave crest and the floating bodies, showing that the peak of the wave is positioned centrally between the catamaran and barge float at this specific phase of wave propagation. Fig. 9 (e) and (f) depict the condition of the two floating bodies after the entire wave has passed. However, analysing a single simulation image cannot conclusively determine the advantages and disadvantages of the two floating bodies. Both floats must be subjected to various wave conditions to undergo comprehensive testing and data analysis.

The floating body demonstrating improved motion characteristics under the same wave conditions should be selected. The primary criteria for selection are the changes in pitch angle, the amplitude of motion along the heave axis, and the tension in the mooring line. RAO (Response Amplitude Operator) is a dimensionless parameter that describes the dynamic response characteristics of marine structures such as ships and floating platforms under external excitation like waves and

wind. It is the ratio of the structure's response amplitude to the external excitation amplitude and is typically used to analyse the behaviour of the structure under different frequencies (Skandali et al., 2020). The motions induced by waves in floating solar structures are discussed regarding heave and pitch movements. As defined in equations (8) and (9) (Huang and Thomas, 2019), the corresponding motion amplitudes are quantified using RAOs. These RAO serve as indicators, expressing the ratio of the motion amplitudes of a floating body to the initiating amplitudes of the incoming waves. By using RAO, the motion response of the structure in various sea conditions can be evaluated, helping to optimise the design, reduce wave-induced motions, and ensure the structure's safety in harsh environments (O'Donnell et al., 2020).

$$RAO_{heave} = \frac{A_z}{A} \quad (8)$$

$$RAO_{pitch} = \frac{\theta_y}{kA} \quad (9)$$

Where $A = H/2$ represents the amplitude of the incident wave, H denotes the wave height and $k = 2\pi/\lambda$ denotes the wavenumber, A_z and θ_y are the amplitudes of the heave and pitch motions respectively.

Both the pitch angle and the motion amplitude of the heave axis provide good indicators of the floating body's motion response. Additionally, the tension of the mooring line can be used to analyse further and re-optimize the structure. Mooring force is provided by two load sensors attached to the front anchor chain.

3. Validation

3.1. Wave tank experiments

Wave tests of floating bodies were conducted at the Cranfield Wave Tank to confirm the validity of the proposed CFD approach. The

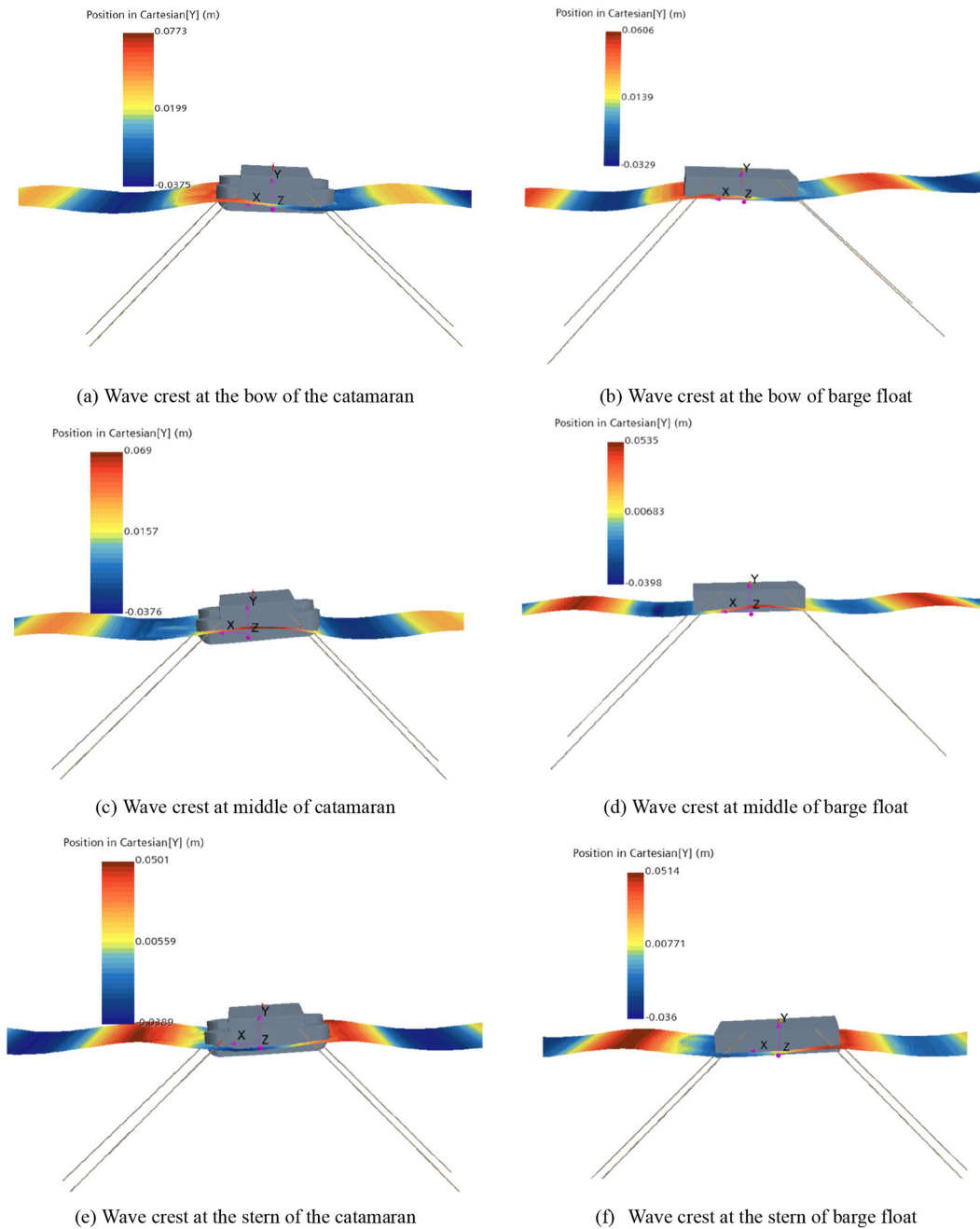


Fig. 9. Floating body performance during wave-induced motions ($\lambda = 1.62$).

experimental wave tank has a length (L), width (W), and water depth (D), as shown in Fig. 10. First, according to the model's size, the catamaran floating body and the barge floating body are prepared according to the exact specifications. The specifications are shown in Table 1. The catamaran and the barge floating body have the exact dimensions: a length of 1m, a width of 0.66 m, and a height of 0.2 m. The floating bodies are made from Styrofoam CM20BE with a density of 28 kg/m^3 .

Additionally, the upper support assembly has a fixed weight of 11.53 kg. The floating body will be positioned in the middle of the wave tank, using a dumbbell plate as the weight anchor and fishing line as the mooring line to connect the floating body to the dumbbell plate. The mooring line must be pre-tensioned to keep the floating body in place. The specific setup parameters are consistent with those in the simulation computing domain and are illustrated in Table 2. The angle between the mooring line and the floating body is maintained at 45° , and the length

of the anchor chain is 2.2 m. Two inclinometers are positioned at the front and rear of the photovoltaic panel to measure inclination data and cross-calibrate each other. A load sensor is attached at the top of the mooring line, connecting to the floating body to calculate the required force. Fig. 11 shows both floating bodies in the experiment wave tank.

Both floating bodies were tested under various wave conditions while maintaining the same water depth. Load sensors monitor the mooring force data in real time as the waves change. The inclinometers record the motion data.

Table 4 lists the experiments scheduled under varying wave conditions in the tank. Five frequency scenarios range from 0.6 Hz to 1 Hz, with each incrementing by 0.1 Hz. The wave heights are set at only 5 cm and 10 cm. Therefore, ten experiments should be conducted for each floating body, excluding repeated experiments for checking replicability (Yang et al., 2024).

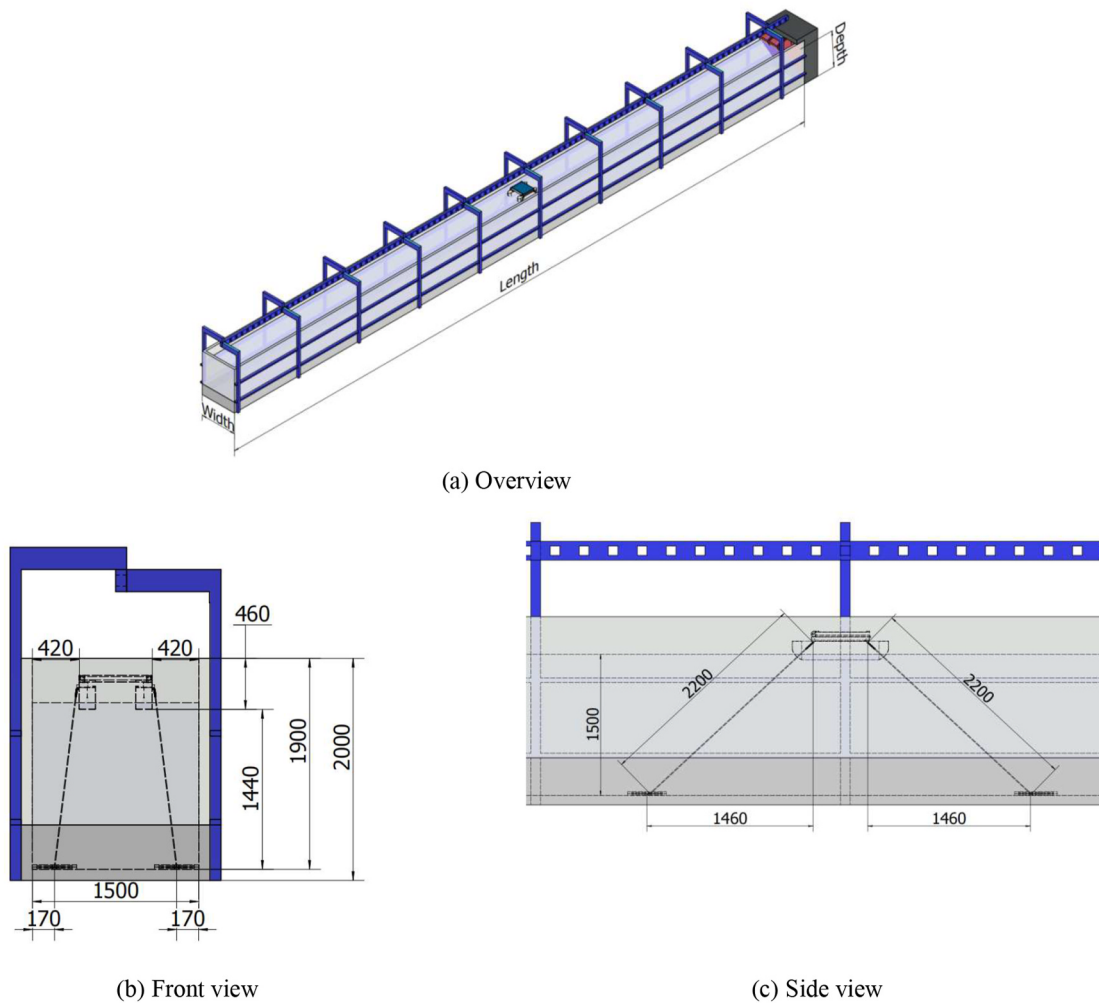


Fig. 10. Experiment wave tank dimensions (Huang et al., 2024).

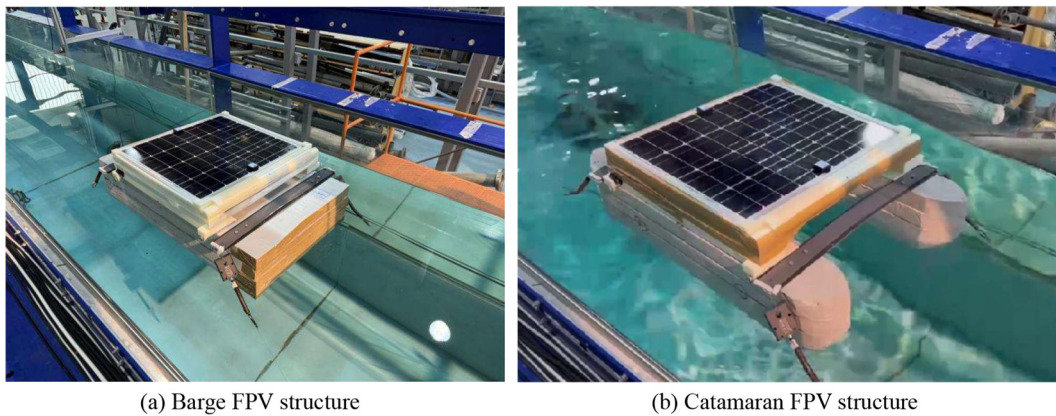


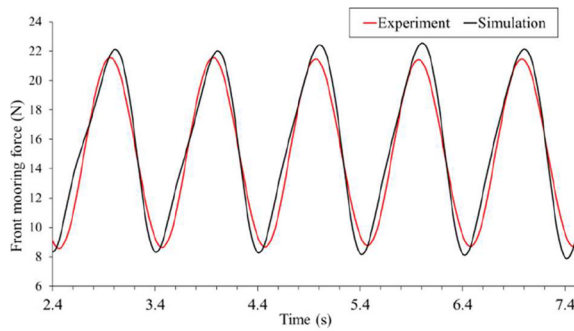
Fig. 11. FPV structures in an experiment wave tank.

3.2. Comparison between experiment and simulation

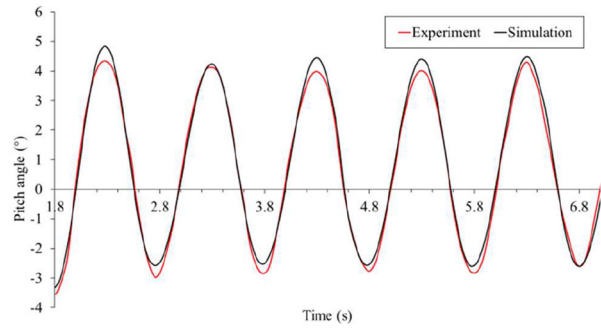
Simulations were performed to replicate the experimental tests. The CFD simulation was performed using STAR-CCM + software, and the simulation data was compared with the experimental data. Numerical parameters were systematically adjusted until simulation predictions agreed with experimental measurements within 10% for motion amplitudes and mooring forces. Accurate simulation settings can be used in

the subsequent design of multi-body structures and multi-body connections, such as joint forces and multi-body structure response.

Fig. 12 (a) compares the simulated and experimental results of the anchor chain force at the front of a flat floating body in waves with a frequency of 1 Hz and a wave height of 10 cm. The left vertical axis represents the front side mooring force, while the horizontal axis represents time. The experimental data line shows that the peak anchor chain force is 21N, and the valley value is 9N, with an amplitude of



(a): Comparison of front mooring force between experiment and CFD simulation



(b): Comparison of pitch angle between experiment and CFD simulation

Fig. 12. Comparison between experiment and CFD simulation under 1 Hz and 10 cm wave height (barge float).

approximately 6 N. In comparison, the simulated data shows more significant fluctuation, with the peak force reaching around 23 N at 2 s, likely due to the flow field not being fully stabilised and the results still needing to be completely converged. After convergence, the simulation results are slightly larger than the experimental values, with the peak force reaching 22 N and the lows around 8.5 N.

Fig. 12 (b) compares pitch angle results between the experiment and the simulation for a barge float floating body with a wave height of 10 cm and a frequency of 1 Hz. The figure shows that the valley value of the experimental pitch angle is slightly larger than that of the simulation. They compare the pitch angle curve between the experiment and the simulation. The result is a coincidence; only some differences appear in peak and valley values. The most significant discrepancy occurs at the peak of the first curve, where the difference does not exceed 1° . This minimal variation is sufficient to demonstrate that the simulation results are in good agreement with the experimental data.

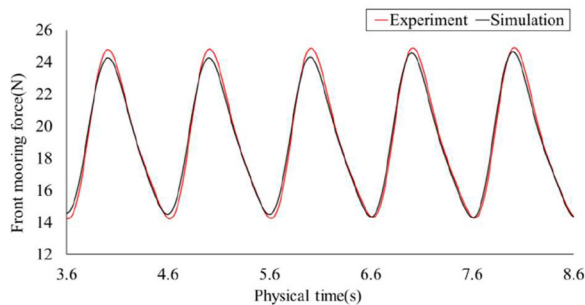
Fig. 13 (a) illustrates the time variation of the front anchor chain force for the catamaran floating body in waves with a height of 10 cm and a frequency of 1 Hz. The solid black lines represent the simulation results, while the solid red lines depict the experimental results. As shown in the figure, during the initial wave-induced motions in the simulation, the floating body had not yet reached a stable, converged state, leading to a significant discrepancy between the simulation and experimental results. When comparing this to the front mooring force of the barge's floating body, it becomes evident that the catamaran's front mooring force amplitude is notably larger. This suggests that the catamaran requires stiffer mooring lines for secure anchoring under these wave conditions.

Fig. 13 (b) illustrates the comparison between the pitch angle of the catamaran floating body observed in the experiment and the simulated

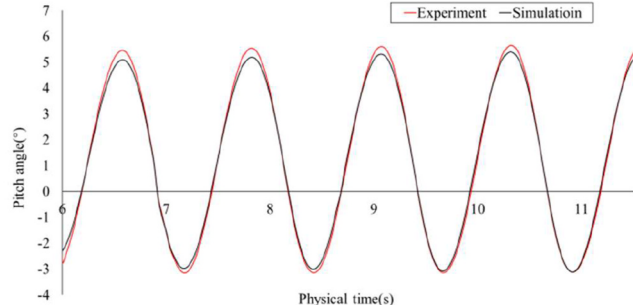
pitch angle. The figure reveals a close alignment between the experimental and simulated results, with both showing similar trends. The variation in pitch angles between the two methods is relatively minor, with only a slight difference in amplitude, indicating a high level of agreement between the simulation and experimental data.

All simulation results across various cases were compared with the experimental outcomes, as depicted in Fig. 14 the vertical axis represents the amplitude of the front-end cable force. In contrast, the horizontal axis shows the wavelength divided by the length of the floating body. Red and black colour differentiate between the experiment and simulation, with red indicating the experiment and black representing the simulation. All the symbols represent the experiment results. This distinction between symbols and lines allows for a clear comparison between each floating body's simulation and experimental outcomes. This dimensionless representation allows for consistently comparing the interactions between different wavelengths and floating body types. Five different wave frequencies were tested, ranging from 0.6 Hz to 1 Hz during the experiment, with the corresponding wavelengths from 1.62 m to 4.27 m, to more clearly and quantitatively show the difference of the simulation, take the cases with $h = 10$ cm as an example, the percentage of difference is calculated and presented in Table 7.

As shown in the comparison of the mooring forces, when the wavelength is 1.6 times the length of the floating body, the mooring line of the barge float experiences more force than that of the catamaran, regardless of whether the wave amplitude is 5 cm or 2.5 cm. However, as the ratio of the wavelength to the length of the floating body increases to 3.21 times, the catamaran's mooring line is subjected to more force than the barge float at both 5 cm and 2.5 cm wave amplitudes. For a 5 cm wave amplitude, the catamaran's front mooring force reaches 18.34 N, whereas the barge float experiences only 12.15 N, a difference of 34%.



(a): Comparison of front mooring force between experiment and CFD simulation



(b): Comparison of pitch angle between experiment and CFD simulation

Fig. 13. Comparison between experiment and CFD simulation under 1 Hz and 10 cm wave height (Catamaran)

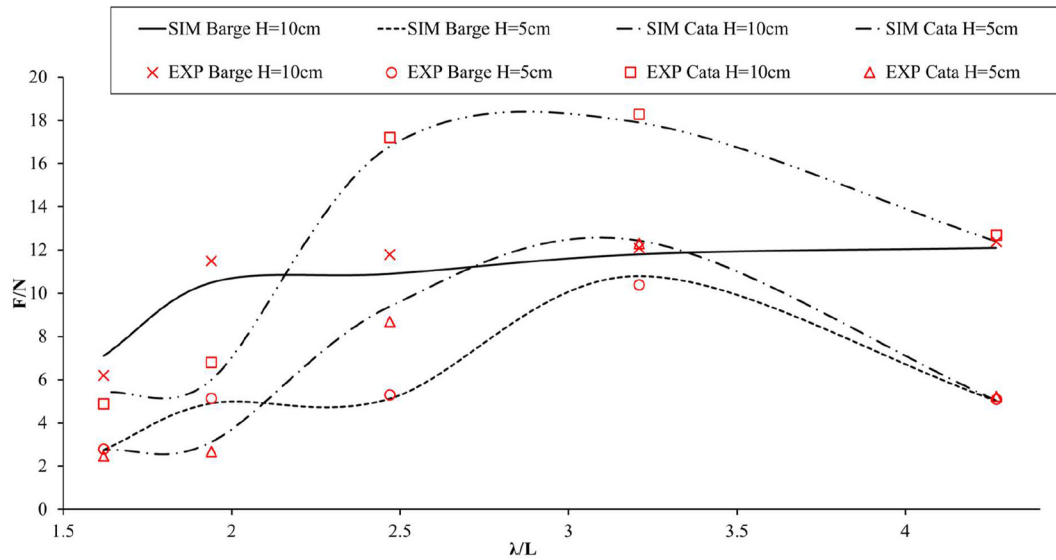


Fig. 14. Comparison of mooring force between experiment and simulation.

Table 7

The mooring force difference between simulation and experiment under $H = 10$ cm.

Wave condition (λ/L)	Experiment mooring tension (N)		Simulation mooring tension(N)		Difference	
	Barge	Catamaran	Barge	Catamaran	Barge	Catamaran
4.27	12.43	12.71	12.11	12.44	2.5%	2.1%
3.21	12.15	18.34	11.83	17.96	2.4%	2.3%
2.47	11.80	17.28	10.94	16.84	7.6%	2.2%
1.94	11.54	6.83	10.51	6.21	8.9%	9.1%
1.62	6.41	4.94	7.07	5.21	9.5%	5.5%

Additionally, when the wave amplitude is 5 cm, it can be observed that the anchor chain force for the barge float remains stable when the wavelength exceeds 2.47 times its length. In contrast, the catamaran structure experiences more force than the barge float until the wavelength reaches 4.27 times its length. This suggests that catamaran structures require more stable anchoring and stiffer mooring lines in long-wavelength environments. Overall, at the same wavelength but with different wave heights, the barge float's mooring line is subjected

to less force than the catamaran.

The simulation results for the catamaran floating body and the barge float floating body were compared with the experimental results under the same case conditions. Both sets of simulation results showed minimal error when compared to the experimental data. As shown in figures, the difference between the simulation and experimental results is minimal, with the deviation of the simulation results being less than 10%.

However, in photovoltaic applications, the mooring line force is just

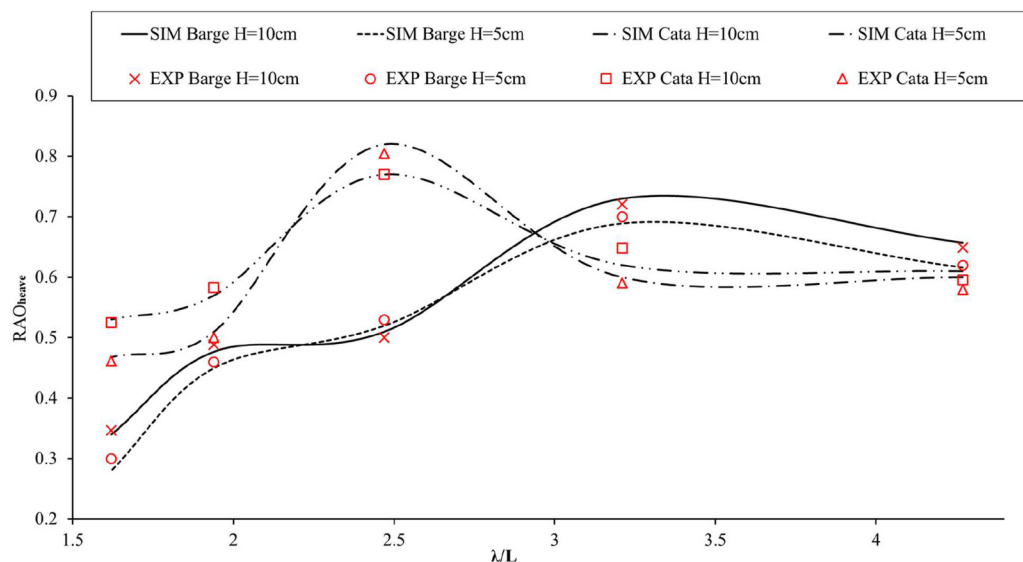


Fig. 15. Comparison of RAO_{heave} between experiment and simulation.

one of the design considerations, with the primary focus being the motion response of the floating body. Reduced motion amplitudes help maintain optimal panel orientation for power generation. A floating body with poor seakeeping characteristics can lead to reduced efficiency in photovoltaic power production. Therefore, investing in stiffer mooring lines to ensure enhanced performance and reliability would be worthwhile if a catamaran float could offer improved motion response.

The RAO was employed to analyse the heave motion data across all test cases for both floating bodies in Fig. 15. When the wavelength is 1.62 times the floating body's length, the barge float's RAO_{heave} remains consistently lower than that of the catamaran under identical wave conditions. As the ratio of the wavelength to the length of the floating body progressively increases, the RAO_{heave} of the barge float increases, indicating a corresponding intensification in its heave motion as the wavelength grows.

Conversely, the RAO_{heave} of the catamaran peaks when the wavelength-to-floating body length ratio is 2.47. At a wave height of 5 cm, the catamaran's RAO_{heave} attains a value of approximately 0.8, signifying that its heave motion equals 80% of the wave amplitude. The peak in heave response at $\lambda/L = 2.47$ indicates a possible resonant condition where the wave excitation frequency approaches the float's natural frequency in heave. Once the wavelength exceeds 2.47 times the length of the catamaran, the RAO_{heave} declines as the wavelength further increases, demonstrating a reduction in heave motion. Beyond this point, under the same wave height and wavelength conditions, when the wavelength exceeds 2.47 times the structural length, the catamaran's heave response becomes smaller and more stable than the barge float, indicating reduced motion response in more extended wavelength environments.

The typically percentage of the difference of RAO_{heave} at $H = 10$ cm wave height is given in Table 8.

The variation in pitch angle is a critical factor that warrants careful consideration. A stable pitch angle ensures a more consistent and reliable power output from the photovoltaic system. Conversely, excessive pitch angles can jeopardise the structural motion response of the floating body, potentially leading to in motion response or, in extreme scenarios, capsizing. The results of RAO_{pitch} is given in Fig. 16 for the barge float and catamaran under 5 cm and 10 cm wave height.

Fig. 16 illustrates the trend of RAO_{pitch} variation as a function of the ratio between wavelength and the length of the floating bodies. The solid lines represent the simulation data, while the symbols correspond to the experiment results. The figure shows that for the barge float, the pitch angle increases with the wavelength under a wave height of 10 cm and reaches a peak value at a wavelength ratio of 3.21. After that, it starts to decrease. For a wave height of 5 cm, the pitch angle peaks at a wavelength ratio of 2.47, followed by a slight reduction and stabilisation. Conversely, the pitch angle of the catamaran initially rises with increasing wavelength, peaking when the wavelength reaches 2.5 times the length of the floating body before undergoing a rapid decline. The pitch RAO decreases with increasing wavelength ratio for both configurations, consistent with typical floating body behaviour in long waves where hydrostatic restoring dominates. Under short-wavelength conditions, the catamaran exhibits a significantly larger pitch angle than the barge float. In contrast, under long-wavelength conditions, the catamaran displays a smaller pitch angle relative to the barge float. The

differences between the experiment and simulation results are given in Table 9.

Catamaran floats tend to outperform barge floats for regions with relatively stable wave conditions, such as nearshore areas. However, barge float floats exhibit better overall performance as the wavelength shortens and the wave frequency increases. Therefore, the choice of floating body design should be based on the floating solar farm's geographical location and wave characteristics.

The response of a single floating body cannot be solely used to assess the overall efficacy of a floating structure. Barge float floats are better suited for multi-body and modular designs, such as hinged configurations or designs directly integrated into maintenance channels. In contrast, catamaran floats lack these advantages. Additionally, in natural environments where waves can approach from multiple directions, catamaran floats do not possess a significant advantage over barge floats when waves strike from the side. When catamaran floats are linked in a multi-body configuration, the potential for generating additional eddy currents may arise, leading to unwanted motion.

In conclusion, it is essential to conduct simulations and testing on multi-body structures for both floating body designs to assess their performance in various conditions thoroughly.

4. Multi-body study

After evaluating a single float, the subsequent phase involves testing multi-body floats. Experiments often face constraints to test multi-body configurations due to sizes. Simulation can address these limitations. The small error margin proved between the simulation results and the experimental outcomes of a single floating body, which falls within an acceptable range, validates the use of simulations for subsequent multi-body configurations. Both catamarans and barge floating bodies are viable for multi-body connections. Given the typically large scale of photovoltaic fields in practical scenarios and the limitations of computer resources, a series of simulations will be conducted, starting with a 1×3 multi-body configuration.

Data derived from these simulations will inform the design and planning of photovoltaic fields. This includes analysing variations such as the difference in tension between the connecting line chain and the anchoring cable chain, discrepancies in pitch angles and motion between the central floating body and the peripheral floats in waves. Finally, determine whether a catamaran or barge float is more suitable for the FPV plant base floating body structure.

4.1. Multi-body structure of 1×3 floating bodies

Each float is moored at 45° to the incident wave direction using bow and stern lines anchored to the seabed. The middle floating body is linked solely to the front and rear floating bodies. The length of the entire simulated domain remains consistent with that of the experiment wave tank. Both the front and rear mooring lines are set with a preload of 20 N, identical to the conditions in the single-unit experiment. Each floating body is spaced 50 cm apart and interconnected by mooring lines. The computational domain has been shown in Fig. 3.

The primary concern in the design of floating photovoltaic systems is the pitch angle, as this directly affects the energy generation efficiency

Table 8

The RAO_{heave} difference between simulation and experiment under $H = 10$ cm.

Wave condition (λ/L)	Experiment RAO_{heave}		Simulation RAO_{heave}		Difference	
	Barge	Catamaran	Barge	Catamaran	Barge	Catamaran
4.27	0.649	0.596	0.667	0.614	2.7°%	3.0°%
3.21	0.721	0.648	0.736	0.631	2.1°%	2.6°%
2.47	0.532	0.770	0.514	0.743	3.4°%	3.5°%
1.94	0.488	0.583	0.453	0.539	7.2°%	7.5°%
1.62	0.347	0.525	0.321	0.542	7.5°%	3.2°%

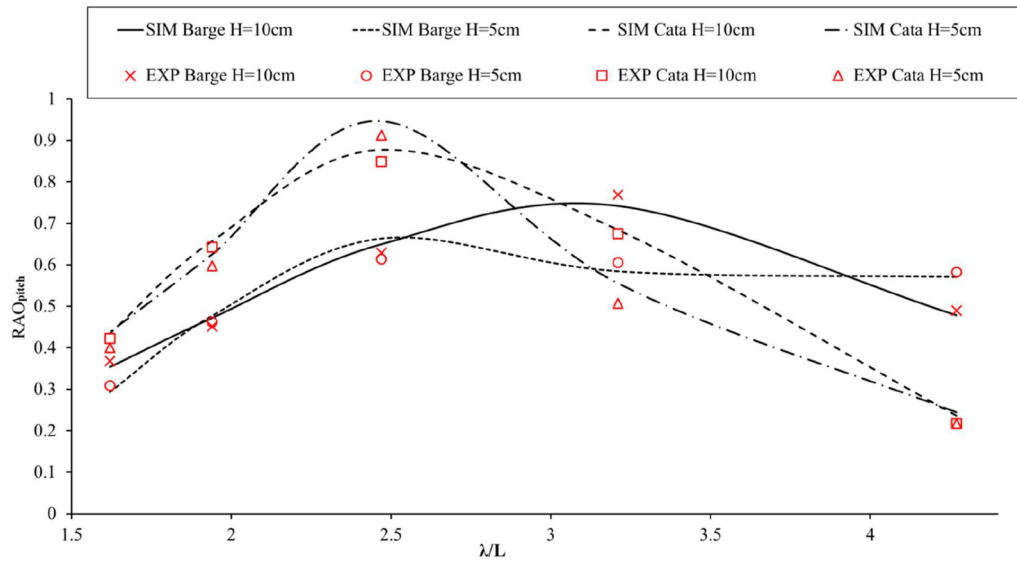


Fig. 16. Comparison of RAO_{pitch} between experiment and simulation.

Table 9

The RAO_{pitch} difference between simulation and experiment under $H = 10$ cm.

Wave condition (λ/L)	Experiment RAO_{pitch}		Simulation RAO_{pitch}		Difference	
	Barge	Catamaran	Barge	Catamaran	Barge	Catamaran
4.27	0.489	0.217	0.478	0.237	2.2%	8.7%
3.21	0.768	0.674	0.742	0.685	3.5%	1.5%
2.47	0.629	0.849	0.649	0.878	3.3%	3.3%
1.94	0.451	0.642	0.472	0.657	4.7%	2.3%
1.62	0.368	0.423	0.353	0.434	3.9%	2.7%

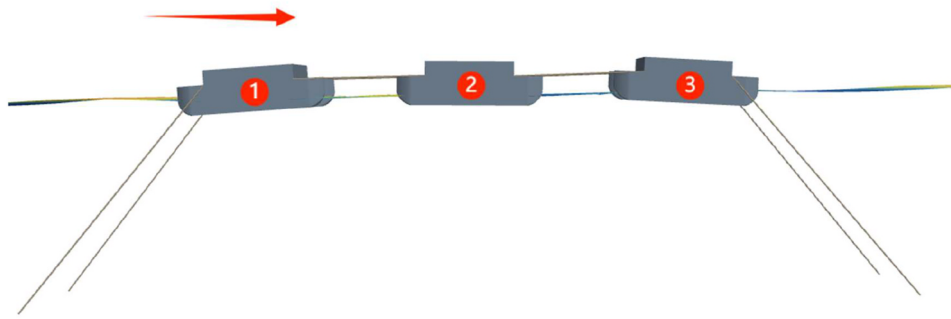
of the photovoltaic modules. Significant variations in pitch angle can result in sub-optimal sunlight exposure, thereby reducing the overall power output (Huang et al., 2024).

Fig. 17 illustrates the catamaran multi-body structure, explicitly showing the response of the three floating bodies in terms of pitch angle in waves with a height of 10 cm and wavelength ratio of 3.21. The three floating bodies, arranged from front to back, are labelled as Body-1, Body-2, and Body-3, with Body-1 being the closest to the incoming wave direction (leading float). The three floating bodies exhibit varying pitch angles in response to the incoming waves. Body-1, the first to encounter the waves, experiences a pitch angle ranging between -2 and -4° , indicating it is leaning forward. Body 2 has a pitch angle oscillating between 2 and -2° , reflecting a more neutral position. Meanwhile, Body-3 (trailing float) is located at the rear and shows a pitch angle between 2 and 4° , suggesting that it is leaning backwards. This variation in pitch angles across the three floating bodies can be attributed to the mooring design. Body-1 is anchored at the bow of the floating body, while Body-3 is anchored at the stern, both secured by anchor chains. The difference in forces applied to the front and rear anchoring points, compared to the middle mooring force, results in the observed forward lean of Body-1 and the backward lean of Body-3, with Body-2 remaining more balanced between the two.

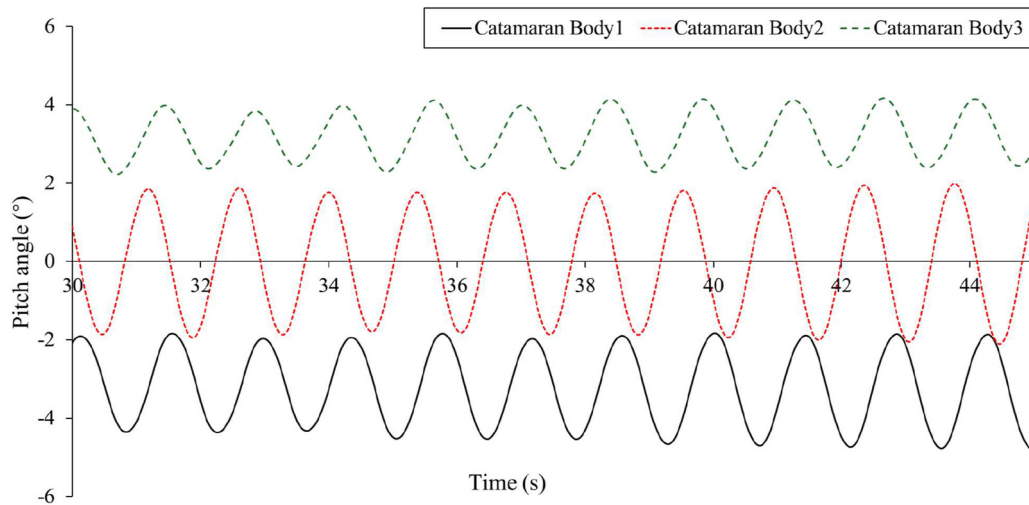
Fig. 18 compares barge and catamaran floats' free surface elevation patterns under a 10 cm wave height at two wavelength ratios, 1.62 wavelength ratio and 4.27 wavelength ratio. Fig. 18 (b) shows the free surface elevation of the catamaran in a short wavelength ratio of 1.62; the catamaran exhibits significantly bright regions with higher elevation around its twin hulls compared to the barge shown in Fig. 18 (a), primarily due to amplified wave diffraction and reflection within the hull gap, where constructive interference and flow acceleration base on Bernoulli effect and elevate local wave crests. The catamaran's dynamic

pitch and heave motions further synchronise with short-wave frequencies, enhancing transient wave-structure interactions. In contrast, the barge's flat, broad geometry distributes wave energy uniformly across its larger waterplane area, suppressing localised elevation extremes and resulting in smoother, lower-amplitude-free surface variations. As the previous single-body simulation results from Figs. 15 and 16 show, the catamaran exhibits higher RAO_{heave} and RAO_{pitch} values compared to the barge at a wavelength ratio of 1.62. This indicates that the catamaran demonstrates more pronounced motion responses under short-wavelength conditions. Fig. 18(c) and (d) show barge and catamaran floaters under 4.27 wavelength ratio; the free surface elevation patterns of both float types exhibit enhanced clarity compared to 1.62 wavelength ratio free surface elevation, as the extended wavelength allows wave-structure interactions to manifest more distinctly across spatial scales. For the barge, the broad, flat hull causes incoming waves to bifurcate symmetrically around its sides, dispersing energy laterally and generating uniform elevation profiles with minimal crest-trough distortion—a behaviour driven by its geometry's innate ability to scatter waves without localised disturbances. In contrast, the catamaran's twin-hull configuration channels a portion of the wave energy through the central gap, while the streamlined bow and stern introduce hydrodynamic interference. At the bow, flow acceleration narrows the passage between the hulls, reducing pressure and creating a stern that forms a low-pressure wake that elevates the free surface. The free surface elevation diagrams reveal distinct differences in how the two geometries interact with waves.

The same method is applied to compare the performance differences between the barge float and the catamaran in a multi-body structure for comparing single-body structures at varying wavelengths. The data is presented in a dimensionless format, where the x -axis represents the wavelength divided by the length of the individual structure. The y -axis



(a) Multi-catamaran side view under 0.7 Hz and 10 cm wave height



(b) Multi-catamaran pitch angle comparison under 0.7 Hz and 10 cm wave height

Fig. 17. Multi-catamaran under 0.7 Hz and 10 cm wave height.

represents the amplitude of the pitch angle, denoted as θ . Fig. 18 compares the catamaran and barge float structures Body-1, Body-2, and Body-3. The solid red line in the figure represents the barge float, and the dotted black line represents the catamaran. The different shapes correspond to each floating body: squares represent Body 1, triangles represent Body 2, and crosses represent Body 3.

The multi-body relationship between wavelength ratio (λ/L) and RAO_{pitch} under 10 cm wave height is given in Fig. 19. It can be observed from the figure that as the wavelength ratio increases, the response of the RAO_{pitch} of all floating bodies gradually increases. The response amplitude increases with wavelength ratio, indicating stronger wave-structure interaction in longer waves. At the same wavelength ratio, the RAO_{pitch} of the barge float floating body is generally higher than that of the catamaran floating body, especially in the more extended wavelength region, which indicates that the barge float floating body has a stronger response ability under wave excitation. In addition, when the wavelength region is smaller than the 2.47 wavelength ratio, the catamaran appears to have a stronger response ability than barge float. The catamaran bodies 1, 2 and 3 all have larger RAO_{pitch} than barge float under a small wavelength ratio. Fig. 20 shows the CFD visualisation results in comparison between 1×3 multi-body structure between catamaran and barge float under 10 cm wave height and 1 Hz, which is a 1.62 wavelength ratio. The visualisation captures the moment the leading float (Body 1) encounters the wave crest after stabilising the flow field. The visualisation of the structure performance in Fig. 20 also proves the accuracy of the RAO_{pitch} results. As shown from Fig. 20 (a)

and (b), the catamaran Body 1 has a larger pitch angle than the barge float Body 1. The head of Body 1 of the catamaran is sinking, while the head of Body 3 has an increased elevation. The catamaran configuration shows higher motion response amplitudes in short waves ($\lambda/L < 2$), with RAO values approximately 15% higher than the barge float. Fig. 20 (c) and (d) show the behaviour of the two floating bodies at 0.6 Hz, which is a long wavelength. As can be seen from the figure, the catamaran exhibits an entirely different response than it does under the shortwave. Catamaran body 1 did not show a significant pitching motion, but body 3 showed a significant upward movement. At the same time, body 3 of the barge float also showed an apparent upward phenomenon. Compared with the RAO_{pitch} figure, it is found that at 0.6 Hz, the wavelength ratio of 4.27, the RAO_{pitch} difference between a catamaran and a barge float is not much, both around 0.2. This also shows there is little difference in pitch behaviour of both shapes Body 3 under long wavelength. The most significant gap was body 1, where the RAO_{pitch} of Body 1 on a barge float far exceeded that of the catamaran. This can also be confirmed in Fig. 20.

The RAO_{pitch} of catamaran Body 1, catamaran Body 2 and catamaran Body 3 show different responses with the increase of wavelength ratio, but the overall value is lower. This may indicate that catamarans are designed to provide better motion response to some extent, reducing dynamic response to wave action. Barge Body 1, Barge Body 2, and Barge Body 3 show a high RAO_{pitch} response, especially when the wavelength ratio value reaches 3.21; the RAO_{pitch} increases obviously. Body 1 always has the greatest RAO_{pitch} , follow by Body 2 and Body 3.

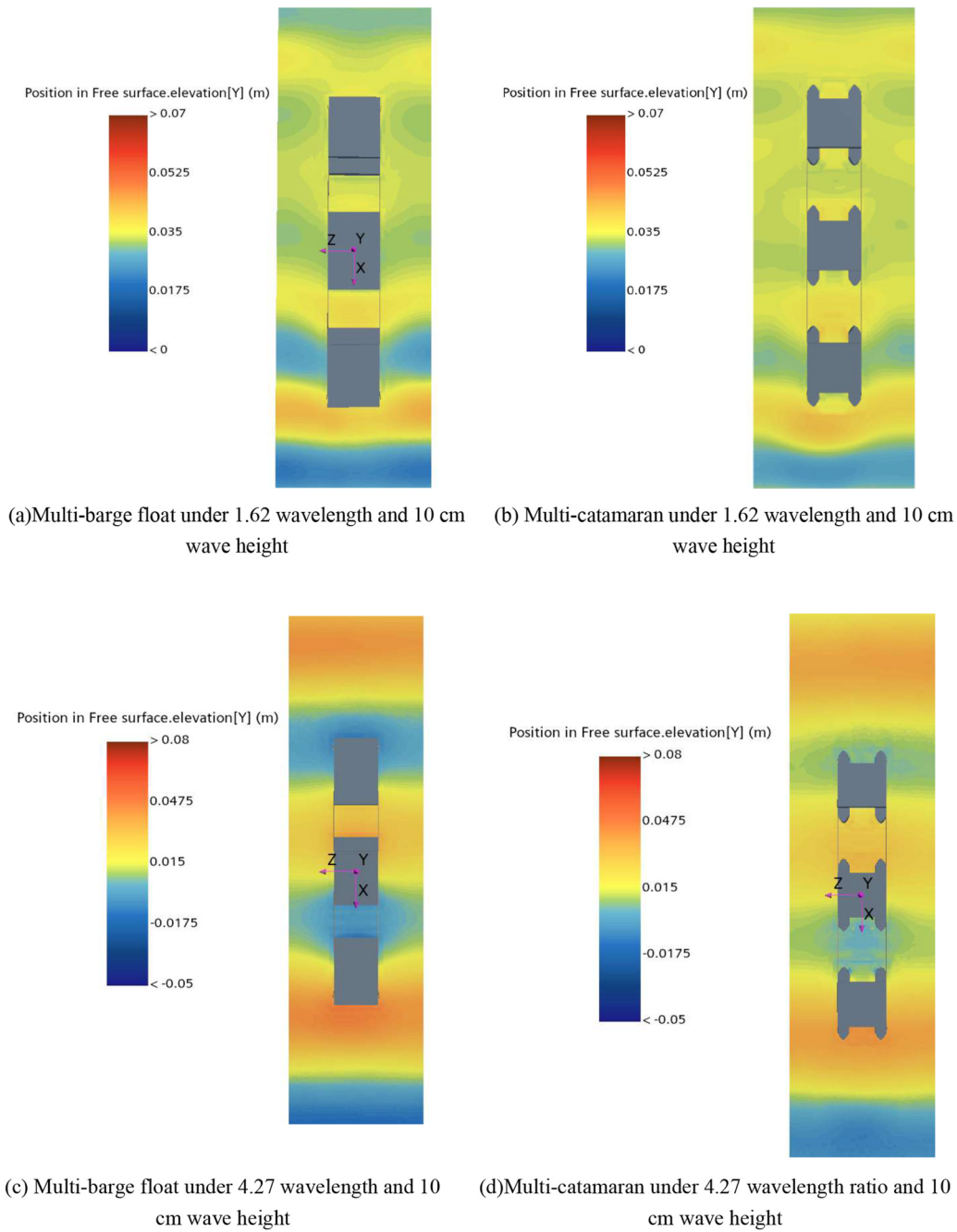


Fig. 18. Multi-body free surface elevation under 10 cm wave height at different wavelength ratio.

The results showed that wave forces on trailing floats are reduced by approximately 30% due to sheltering effects from the leading float. Leading float creates a modified wave field affecting trailing floats.

Fig. 21 presents the RAO for heave motion RAO_{heave} of multi-body floats under a 10 cm wave height. The RAO_{heave} values for both the barge float and catamaran structures increase as the wavelength ratio rises, indicating that heave motion becomes more pronounced in longer wavelength environments, with a stronger wave response. The RAO_{heave} values for the barge float (Barge Body 1, Barge Body 2, and Barge Body 3) are generally higher within the long wavelength ratio range, suggesting a greater propensity for significant heave responses under wave action. This effect is particularly notable when the wavelength ratio reaches 4.27, where the RAO_{heave} approaches 0.45, highlighting the barge float's sensitivity to waves and its higher dynamic response capability.

In contrast, the RAO_{heave} values for the catamaran floating body are consistently lower than those of the barge float, especially in longer wavelength scenarios. Both the RAO_{heave} and RAO_{pitch} results indicate that the catamaran floating body exhibits superior performance compared to the barge float under long-wavelength conditions, demonstrating the considerable potential of catamaran structures in such environments. In addition, Figs. 14 and 15 show the RAO_{heave} and RAO_{pitch} of a single floating body. Catamaran structure RAO increases rapidly when the wavelength ratios are around 2.47 and 3.21, but this situation did not happen in multi-body structures. The inter-float connections provide additional stiffness to the array, resulting in reduced motion amplitudes compared to individual floats.

The Front and middle mooring force amplitude of two different floating bodies under 10 cm wave height are given in Fig. 22. The leading float experiences the highest mooring forces due to direct wave

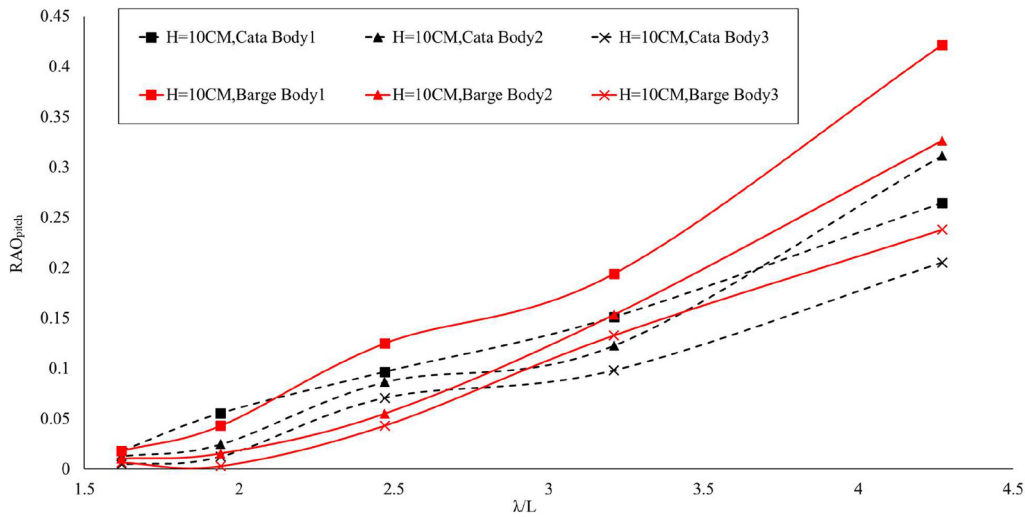


Fig. 19. Comparison of RAO_{pitch} between catamaran/barge float multi-body structures.

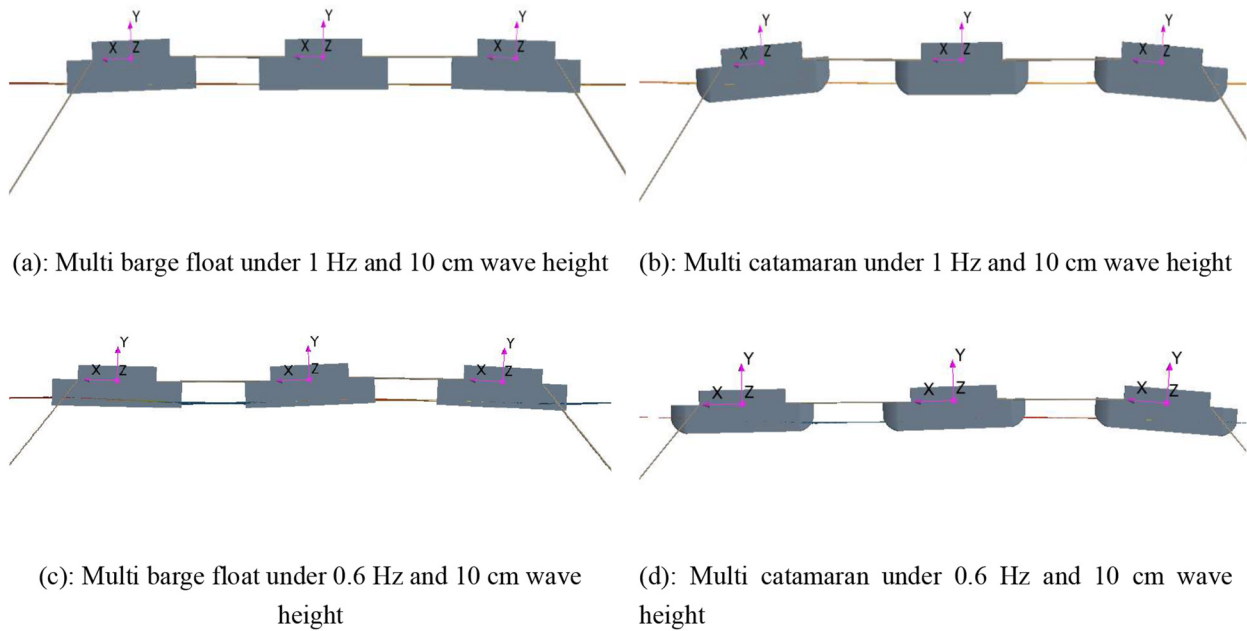


Fig. 20. Multi-body visualisation performance under 10 cm wave height at different frequencies.

excitation, while internal connection forces between floats show lower amplitudes due to motion phase differences. As the wavelength ratio increases, the mooring force also rises, suggesting that a long wave demands greater tension force.

Additionally, the mooring force for the barge float floating body escalates rapidly with increasing wavelength. At the maximum wavelength ratio of 4.27, the front mooring force of the barge float is nearly double that of the catamaran. For smaller wavelength ratios, such as 1.62 and 1.94, the front mooring force of the catamaran exceeds that of the barge float.

These findings align with the RAO results, reinforcing that barge floats are more responsive to wave action and exhibit greater pitch angles and heave motion under long-wavelength conditions, consequently requiring higher mooring forces for station-keeping. In contrast, catamarans demonstrate superior performance in long-wave environments, characterised by lower RAO values and reduced mooring forces.

5. Conclusions

This study has examined the motion response characteristics of twin-hull and barge float configurations for floating solar applications through CFD analysis, supported by experimental validation. The CFD predictions showed good agreement with wave tank measurements, with motion response differences typically within 10% for various tested conditions, providing confidence in the computational approach for both single and multi-float arrangements.

The comparative analysis revealed distinct differences in float response characteristics that depend strongly on wave conditions. In longer waves ($\lambda/L > 2.47$), the twin-hull configuration demonstrated reduced heave motions compared to barge floats, with heave RAOs approximately 20% lower. However, this advantage diminishes in shorter waves ($\lambda/L < 2$), where the twin-hull design showed increased motion responses. The pitch motion characteristics showed similar trends, where the differences between configurations were less pronounced.

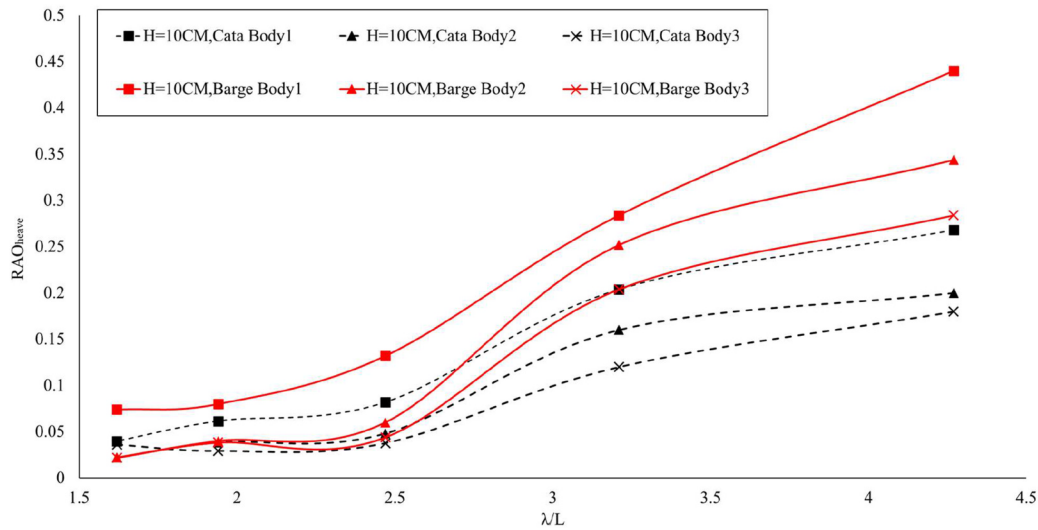


Fig. 21. Comparison of RAO_{heave} between catamaran/barge float multi-body structures.

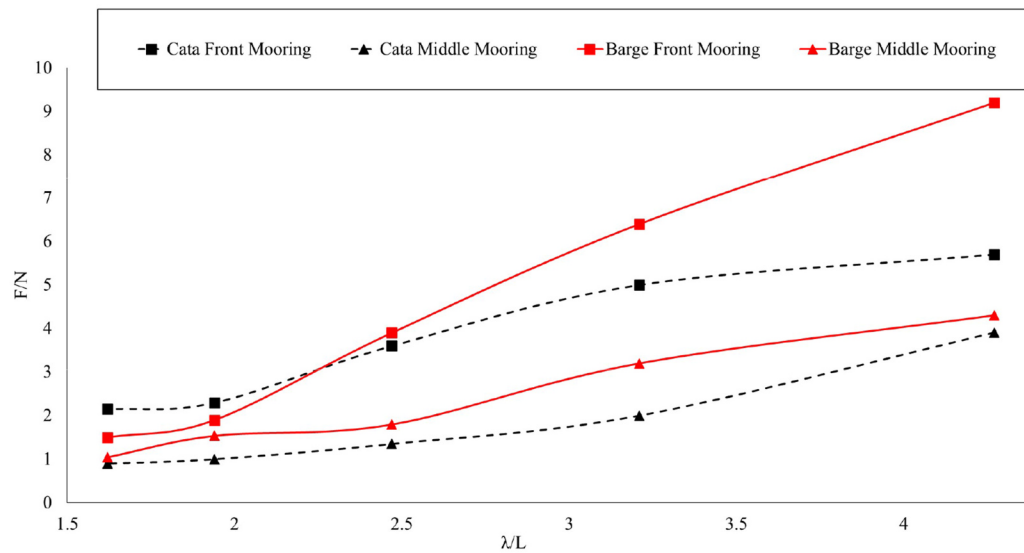


Fig. 22. Comparison of mooring force amplitude between catamaran/barge float multi-body structures.

The investigation of three-float arrays revealed significant hydrodynamic interaction effects. The leading floater consistently experienced higher motion responses and mooring loads than the trailing floaters, with forces up to 30% greater under the tested wave conditions. Meanwhile, the middle floater demonstrated larger motion responses than the rear floater, so the rear floater experienced the least wave excitation forces and motion responses. This reduced load on the rear float can be attributed to the shielding effects of front floaters and the suspension of rear mooring lines.

These findings have practical implications for FPV system design, with its novelty of comparing floaters in different wave conditions, and their array performance. The selection of float configuration in industrial projects can be considered based on the expected wave conditions at the installation site. The quantified differences in dynamic responses provide a basis for future design decisions. The present work has focused on regular waves, small wave heights and a 1*3 arrangement. Future research should examine irregular wave conditions and higher waves, investigate broader ranges of float spacing, study 3*3 and other arrays, and consider the effects of different mooring arrangements. Additionally, fatigue analysis based on the forces obtained on connections and

moorings will be important for the long-term survivability of FPV systems on the ocean.

CRediT authorship contribution statement

Binjian Ou: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Burak Can Cerik:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Luofeng Huang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

Declaration of competing interest

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

Acknowledgements

L.H. acknowledges grants received from Innovate UK (No. 10048187, 10079774, 10081314), the Royal Society (IEC\NSFC\223253, RG\R2\232462) and UK Department for Transport (TRIG2023 – No. 30066).

References

- Al-Yacoubi, A.M., Halim, E.R.B.A., Liew, M.S., 2020. Hydrodynamic analysis of floating offshore solar farms subjected to regular waves. In: Emamian, S.S., Awang, M., Yusof, F. (Eds.), *Advances in Manufacturing Engineering*. Springer, Singapore, pp. 375–390. https://doi.org/10.1007/978-981-15-5753-8_35.
- Benites-Munoz, D., Huang, L., Anderlini, E., Marin-Lopez, J.R., Thomas, G., 2020. Hydrodynamic modelling of an oscillating wave surge converter including power take-off. *J. Mar. Sci. Eng.* 8 (10). <https://doi.org/10.3390/jmse8100771>. Art. no. 10.
- Cazzaniga, R., Cicu, M., Rosa-Clot, M., Rosa-Clot, P., Tina, G.M., Ventura, C., 2018. Floating photovoltaic plants: performance analysis and design solutions. *Renew. Sustain. Energy Rev.* 81, 1730–1741. <https://doi.org/10.1016/j.rser.2017.05.269>.
- Chen, H., Qian, L., Cao, D., 2023. Analysis of convergence behavior for the overset mesh based numerical wave tank in openfoam. *J. Offshore Mech. Arctic Eng.* 146, 031901. <https://doi.org/10.1115/1.4063265>.
- Claus, R., López, M., 2022. Key issues in the design of floating photovoltaic structures for the marine environment. *Renew. Sustain. Energy Rev.* 164, 112502. <https://doi.org/10.1016/j.rser.2022.112502>.
- Cutler, J., Bashir, M., Yang, Y., 2022. Preliminary development of a novel catamaran floating offshore wind turbine platform and assessment of dynamic behaviours for intermediate water depth application. *Ocean Eng.* 258, 111769. <https://doi.org/10.1016/j.oceaneng.2022.111769>.
- Ferziger, J.H., Perić, M., Street, R.L., 2019. *Computational Methods for Fluid Dynamics*. Springer.
- Ghigo, A., Faraggiana, E., Sirigu, M., Mattiazio, G., Bracco, G., 2022. Design and analysis of a floating photovoltaic system for offshore installation: the case study of Lampedusa. *Energies* 15 (23). <https://doi.org/10.3390/en15238804>. Art. no. 23.
- Haas, J., Khalighi, J., de la Fuente, A., Gerbersdorf, S.U., Nowak, W., Chen, P.-J., 2020. Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. *Energy Convers. Manag.* 206, 112414. <https://doi.org/10.1016/j.enconman.2019.112414>.
- Hirt, C.W., Nichols, B.D., 1981. Volume of fluid (VOF) method for the dynamics of free boundaries. *J. Comput. Phys.* 39 (1), 201–225. [https://doi.org/10.1016/0021-9991\(81\)90145-5](https://doi.org/10.1016/0021-9991(81)90145-5).
- Huang, L., Thomas, G., 2019. Simulation of wave interaction with a circular ice floe. *J. Offshore Mech. Arctic Eng.* 141, 041302. <https://doi.org/10.1115/1.4042096>.
- Huang, L., Yang, Y., Khojasteh, D., Ou, B., Luo, Z., 2024. Floating solar power loss due to motions induced by ocean waves: an experimental study. *Ocean Eng.* 312, 118988. <https://doi.org/10.1016/j.oceaneng.2024.118988>.
- Huang, L., et al., 2025. Developing reliable floating solar systems on seas: a review. *Ocean Eng.* 322, 120525. <https://doi.org/10.1016/j.oceaneng.2025.120525>.
- Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, Part I: technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 39 (3), 1154–1169. <https://doi.org/10.1016/j.enpol.2010.11.040>.
- Maghami, M.R., Hizam, H., Gomes, C., Radzi, M.A., Rezadad, M.I., Hajighorbani, S., 2016. Power loss due to soiling on the solar panel: a review. *Renew. Sustain. Energy Rev.* 59, 1307–1316. <https://doi.org/10.1016/j.rser.2016.01.044>.
- Magkouris, A., Belibassakis, K., Rusu, E., 2021. Hydrodynamic analysis of twin-hull structures supporting floating PV systems in offshore and coastal regions. *Energies* 14 (18). <https://doi.org/10.3390/en14185979>. Art. no. 18.
- Mekonnen, T., Ramayya, V., Bhandari, R., Minaye, E., Tsegay, S., 2023. Techno-economic comparative analysis of floating/on-ground solar PV system for electrification of gilgel Gibe I Auxiliary load in Ethiopia [Online]. Available: <https://repository.ju.edu.et/handle/123456789/9235>. (Accessed 12 October 2024).
- Menter, Florida, 1993. Zonal two equation k- ω turbulence models for Aerodynamic flows. In: 23rd Fluid Dynamics, Plasmadynamics, and Lasers Conference. American Institute of Aeronautics and Astronautics. <https://doi.org/10.2514/6.1993-2906>.
- O'Donnell, D., Murphy, J., Pakrashi, V., 2020. Comparison of response amplitude operator curve generation methods for scaled floating renewable energy platforms in ocean wave basin. *ASME. Letters. Dyn. Syst. Contr.* 1, 021012. <https://doi.org/10.1115/1.4049169>.
- Paterson, E., Wilson, R., Stern, F., 2003. *General-purpose Parallel Unsteady RANS Ship Hydrodynamics Code*. CFDShip-Iowa, p. 115.
- Ramana, C.J., Lim, K.H., Kurnia, J.C., 2024. Towards sustainable power generation: recent advancements in floating photovoltaic technologies. *Renew. Sustain. Energy Rev.* 194, 114322. <https://doi.org/10.1016/j.rser.2024.114322>.
- Rosa-Clot, M., Tina, G.M., 2017. *Submerged and Floating Photovoltaic Systems: Modelling, Design and Case Studies*. Academic Press.
- Sahu, A., Yadav, N., Sudhakar, K., 2016. Floating photovoltaic power plant: a review. *Renew. Sustain. Energy Rev.* 66, 815–824. <https://doi.org/10.1016/j.rser.2016.08.051>.
- Song, J., Imani, H., Yue, J., Yang, S., 2023. Hydrodynamic characteristics of floating photovoltaic systems under ocean loads. *J. Mar. Sci. Eng.* 11 (9). <https://doi.org/10.3390/jmse11091813>. Art. no. 9.
- Skandali, D., Lourens, E., Ogink, R.H.M., 2020. Calibration of response amplitude operators based on measurements of vessel motions and directional wave spectra. *Mar. Struct.* 72, 102774. <https://doi.org/10.1016/j.marstruc.2020.102774>.
- Song, X., Bi, X., Liu, W., Guo, X., 2024. Numerical simulation of a floating offshore wind turbine in wind and waves based on a coupled CFD-FEA approach. *J. Mar. Sci. Eng.* 12 (8). <https://doi.org/10.3390/jmse12081385>. Art. no. 8.
- Spencer, R.S., Macknick, J., Aznar, A., Warren, A., Reese, M.O., 2019. Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the Continental United States. *Environ. Sci. Technol.* 53 (3), 1680–1689. <https://doi.org/10.1021/acs.est.8b04735>.
- Trapani, K., Millar, D.L., 2013. Proposing offshore photovoltaic (PV) technology to the energy mix of the Maltese islands. *Energy Convers. Manag.* 67, 18–26. <https://doi.org/10.1016/j.enconman.2012.10.022>.
- Trapani, K., Redón Santafé, M., 2015. A review of floating photovoltaic installations: 2007–2013. *Prog. Photovoltaics Res. Appl.* 23 (4), 524–532. <https://doi.org/10.1002/pip.2466>.
- van der Zanden, J., et al., 2024. Wave Basin tests of a multi-body floating PV system sheltered by a floating breakwater. *Energies* 17 (9). <https://doi.org/10.3390/en17092059>. Art. no. 9.
- Versteeg, H.K., Malalasekera, W., 2007. *An Introduction to Computational Fluid Dynamics : the Finite Volume Method*, second ed. Pearson/Prentice Hall [Online]. Available: <https://cir.nii.ac.jp/crid/1130282271039303040>. (Accessed 21 October 2024).
- Wang, Z., Li, T., Ren, J., Jin, Q., Zhou, W., 2022. URANS calculation of ship heave and pitch motions in marine simulator based on overset mesh. *J. Mar. Sci. Eng.* 10 (10). <https://doi.org/10.3390/jmse10101374>. Art. no. 10.
- Yang, Y., et al., 2024. A comparative experimental study on the hydrodynamic performance of two floating solar structures with a breakwater in waves. *Sol. Energy* 284, 113029. <https://doi.org/10.1016/j.solener.2024.113029>.
- Zheng, Z., et al., 2024. Motion response and energy harvesting of multi-module floating photovoltaics in seas. *Ocean Eng.* 310, 118760. <https://doi.org/10.1016/j.oceaneng.2024.118760>.
- Introductory Guide to overset simulations [Online]. Available: <https://community.sw.siemens.com/s/article/Introductory-Guide-to-Overset-Simulations>. (Accessed 21 October 2024).



DSpace

<https://dspace.org/>

Seakeeping analysis of catamaran and barge floats for floating solar arrays: a CFD study with experimental validation

Ou, Binjian; Cerik, Burak Can; Huang, Luofeng

2025-05-15

Elsevier

<https://doi.org/10.1016/j.oceaneng.2025.120970>

Ou B, Cerik BC, Huang L. (2025) Seakeeping analysis of catamaran and barge floats for floating solar arrays: a CFD study with experimental validation. Ocean Engineering, Volume 326, May 2025, Article number 120970