Journal of Advanced Research Design 132, Issue 1 (2025) 15-27

Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Hydrodynamic Response Assessment of Floating Photovoltaic System Subjected to Environmental Loadings

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ARTICLE INFO

Article history:
Received 17 January 2025
Received in revised form 10 February 2025
Accepted 2 May 2025
Available online 23 May 2025

Keywords:
Floating photovoltaic systems; solar energy; hydrodynamic forces; hydrodynamics of FPVs; offshore conditions; excel-based analytical model; water depth; wave height; hydrodynamic responses

ABSTRACT

Floating Photovoltaic systems (FPVs) represent a novel integration of solar energy technology with aquatic environments, marking a pivotal advancement in renewable energy applications. This paper introduces a new design for the floating system, specifically engineered to optimize performance under hydrodynamic conditions. Despite the significant focus on the field, the complex hydrodynamics of FPVs, particularly their resilience against varying offshore conditions, remain inadequately explored. This study seeks to bridge this knowledge gap by using an Excel-based analytical model to investigate how changes in design parameters, such as water depth and wave height, affect the surge, heave and pitch responses of the proposed design. Our findings indicate that water depth variations predominantly affect surge movement, while wave height significantly influences all hydrodynamic responses of the floater.

1. Introduction

1.1 Background

The increasing global demand for energy has led to the search for innovative and sustainable energy solutions. Among these, Floating Photovoltaic systems (FPV)s have emerged as a significant innovation, especially useful in areas with limited land availability. Since gaining global attention in 2007, FPVs have been deployed in various countries, including Japan, South Korea, India and the USA, offering a viable alternative to traditional land-based solar installations due to their space-efficient design and the cooling effect of water that potentially enhances energy efficiency [1,2].

Worldwide, there are 643 FPV installations spread across 28 countries, with a notable concentration in Asia—Japan, Taiwan and China—highlighting the technology's global distribution and acceptance [3]. These systems not only optimize unused water bodies but also contribute environmental benefits by reducing water evaporation and limiting algae growth, showcasing their dual advantage of energy production and environmental protection [4-7]. However, FPVs face challenges such as higher installation and maintenance costs and potential impacts on aquatic

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https://doi.org/10.37934/ard.132.1.1527

ecosystems. These issues underline the importance of careful design and assessment to ensure environmental compatibility and resilience to conditions like wind, waves and corrosion [6,8,9]. Despite these challenges, the adoption of FPVs is on an upward trajectory, driven by technological advancements and a growing emphasis on sustainable energy solutions. This optimism is supported by research focused on improving the structural design of FPVs to enhance their efficiency, safety and sustainability, ultimately contributing to global renewable energy goals [10-12].

Combining photovoltaic solar technology with floating platforms creates FPVs, an innovative renewable energy solution especially useful in areas with limited land [13]. FPVs include buoyant structures, anchoring moorings, solar panels and necessary wiring. Notably, using FPVs on water bodies can reduce water evaporation significantly; Australian research found a 40% reduction in reservoir water loss to evaporation [14].

1.2 FPVS Components

The standard assembly of FPVs usually comprise these vital elements: PV modules that harness solar energy, flotation structures that provide buoyancy, potentially auxiliary support structures for the PV modules, a system for mooring and anchoring, along with the required electrical components and storage mechanisms [5]. Additionally, FPV plants can enhance their output by incorporating optional systems such as tracking, cooling, cleaning and storage [15].

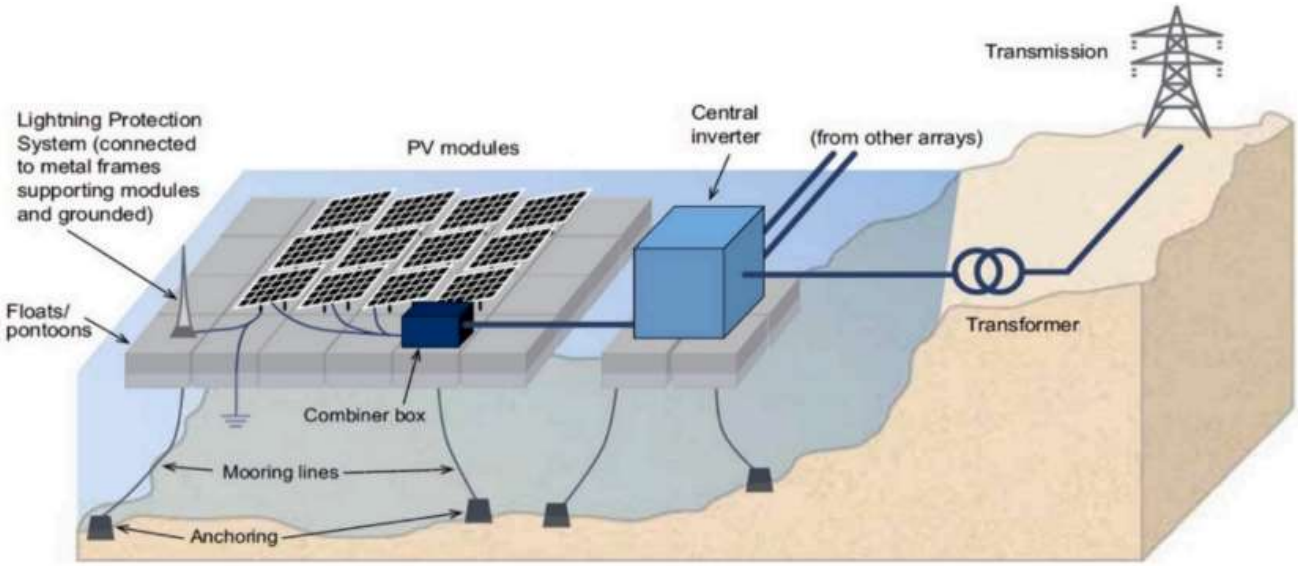

Fig. 1. FPV system components [16]

1.2.1 Floating structures

Floating structures for deploying FPVs on water are classified into three types [17]. "Pure floats" have PV modules mounted directly on floating platforms. "Modular rafts" feature solar panels supported by a structural network attached to floats. Lastly, "membranes" involve panels affixed to a buoyant, reinforced membrane encircled by a tubular ring.

In 2023, a novel application has been proposed to utilize UHPC and FRP in developing a modular floating structure MFS for the FPVs [18]. The proposed MFS applied in the study consisted of a box-pontoon that was connected using hinge connectors. In the same year, another application has been proposed using two layers; a bottom layer made of expanded polystyrene (EPS) and a top layer of ultrahigh performance concrete (UHPC) [19,20]. EPS geofoam, an affordable synthetic material, is characterized by its very low density, high flexibility and corrosion resistance, making it suitable for use in engineering construction.

1.2.2 Mooring system

Mooring types include catenary, compliant, taut and rigid. Catenary uses chain weight for tension; Compliant modifies this with floats and weights. Taut systems maintain line tension, suited for minor water level changes, potentially using adaptable lines like Seaflex®. Rigid moorings, fixed to the seabed, allow heave but limit surge and sway, best for shallow waters [5,15].

1.2.3 Electrical components

Transmitting electricity from FPV plants requires a sophisticated network of cables and electrical devices, favouring above-water installation for easier maintenance despite the need for waterproofing [15]. These components must withstand UV radiation and temperature fluctuations [21]. DC-DC converters adapt to solar power's variability, with inverters integrating the system into the AC grid, often mounted on floating structures for larger projects [22]. Module interconnection is critical for efficiency, as partial shading can decrease energy output by 5-10%, depending on array layout [23].

1.2.4 Efficiency systems

The efficiency of a PV panel is indirectly affected by its surface temperature, with standard PV module specifications indicating that each 1°C increase results in a 0.47% decrease in efficiency [24]. This sensitivity to temperature highlights the importance of cooling mechanisms and optimal positioning to maximize performance. The tracking system, which adjusts panel orientation using active, passive or manual methods, enhances energy yield by optimizing sunlight exposure, a feature particularly valuable in FPV systems that face unique environmental disturbances [15,25]. Additionally, partially submerged FPVs benefit from lower operational temperatures, which have been shown to improve efficiency significantly. Research indicates that these FPVs can generate up to 27.31% more electricity than traditional PV systems without cooling [26].

Complementing these systems, energy storage solutions manage renewable energy variability, with technologies ranging from batteries to hydrogen production. While batteries are widely used, they come with challenges such as high costs and environmental impacts [27]. This integration of tracking, cooling and energy storage enhances the overall efficiency and reliability of PV systems, making FPV technology a promising approach in renewable energy.

1.3 FPV Structural Design

The development of FPV technology currently lacks specific design standards [28]. To address this, adopting design principles from established marine sectors like oil and gas could provide critical guidance for marine FPV systems, leveraging standards on design criteria, environmental conditions and verification for various limit states. The literature highlighted the importance of verifying floating module structural integrity through lab tests evaluating different stress conditions [29]. The marine sector's standards are largely determined by over 50 organizations, including 12 members of the International Association of Classification Societies (IACS), offering a wealth of expertise for the advancement of marine FPV systems [15].

1.4 Offshore Loads

Floating offshore structures are subjected to offshore loads similar to fixed structures, but the dynamics can differ due to their floating nature. The main types of loads affecting floating offshore structures are waves, tides and current [5].

1.4.1 Wave load

Offshore structures encounter substantial forces when they are exposed to waves. In situations where there's an inadequate air gap, wave-related actions, such as buoyancy, inertia, drag and slam must be considered. Ocean waves, given their irregular shape and direction, often present a chaotic pattern of peaks and troughs on the water surface. The direction of these waves is assessed as an average of individual wave directions and is understood to influence the platform from all directions [30].

Wave phenomena challenge mathematical description due to their complex, nonlinear and seemingly random nature. Two foundational theories simplify wave behaviour in deep water: Airy theory (1845) and Stokes theory (1880), while conidial wave theory (1895) applies to shallow waters. The choice of theory for offshore design depends on site-specific conditions like water depth and wave characteristics. Le Méhauté (1976) provided a graph detailing the applicability of various wave theories, guiding engineers in selecting the most appropriate model [31].

Choosing the right theory for calculating wave forces depends on the structure's size relative to the wavelength. If the structure is much smaller, drag forces are significant, making the Morison equations the best fit. For structures substantially larger than the wavelength, where drag forces are negligible, diffraction theory is the more suitable method [31].

Conceptual frameworks for modelling ocean waves date back to the 19th century, but practical theories addressing wave forces on offshore structures emerged only in 1950, marked by the introduction of the Morison equation [31]. Accordingly, the wave forces as per Morison equation consist of drag force and inertia force as follows in Eq. (1) to (3),

$$F_D = {}^{1}/_{2}\, \rho C_d V^2 A \tag{1}$$

$$F_I = {}^{1}/_{4}\, \pi \rho a C_m D^2 \tag{2}$$

$$F = F_D + F_I \tag{3}$$

Where, F_D is the drag force C_d is the drag coefficient (unitless), V is the velocity (m/s), A is the projected Area (m^2), F_I is the inertia force, ρ is the density (kg/m^3), C_m is the mass coefficient (unitless), a is the horizontal acceleration and D is the diameter of the cylinder.

When dealing with large structures compared to the wavelength, Morison's equation may not apply due to significant wave diffraction or scattering, necessitating the consideration of wave diffraction effects in wave-force evaluations. Diffraction theory posits an oscillatory, incompressible and irrotational flow, where fluid velocity is represented as the gradient of a scalar potential, combining incident and scattered potentials for overall velocity potential calculations [32].

The dynamic pressure acting on a structure's body can be calculated based on Bernoulli's equation as follows as in Eq. (4) to (6),

$$p = \sum_{n=1}^{\infty} \varepsilon^n \ p_n \tag{4}$$

$$p_1 = \rho \frac{\partial \Phi_1}{\partial t} \quad (5)$$

$$p_2 = \rho \frac{\partial \Phi_2}{\partial t} + \frac{1}{2}\rho(\nabla\Phi_1)^2 \quad (6)$$

Where, $\varepsilon = kH/2$, *k*= wave number, *H*= wave height, *Φ*= the potential velocity, *p*= pressure and *ρ*= fluid density. After the pressure is obtained, the force on the relative direction can be computed as follows in Eq. (7),

$$F_{nj} = \varepsilon^n \iint_s p_n n_j dS \quad (7)$$

More details are explained by Chakrabarti [32].

1.4.2 Current load

In marine environments, currents significantly impact FPV installations, exhibiting complex profiles that can alter wave conditions and affect coastal areas [33]. These currents, including oceanic, tidal, wind-generated and wave-induced types, necessitate detailed analysis due to potential issues like drift, drag forces, vortex-induced vibrations and seabed erosion, which could impact mooring systems. While currents exert less dynamic pressure than wind, their forces are critical and require precise estimation, possible through experimental, computational fluid dynamics (CFD) or hybrid methods [34]. Methodologies from the broader offshore industry, including experimental tests and CFD models, offer valuable insights for assessing current impacts on FPV systems [35].

1.5 Floating Structure Dynamics

There are two basic approaches to describe the floating structure dynamics [32]:

i. Frequency Domain Analysis: Focuses on structural responses to sinusoidal waves, using response amplitude operators (RAOs), but cannot handle nonlinearities in motion equations.
ii. Time Domain Analysis: Addresses responses to time-varying loads, ideal for nonlinear issues or specific wave sequences, but faces increased complexity and extended analysis time.

1.5.1 Response amplitude operators

According to Chakrabarti [32], the structure's reactions to surge, heave and pitch motions are determined by multiplying the wave energy spectrum with the squared RAO function. The RAO formula can be derived as follows in Eq. (8),

$$RAO = \frac{F/_{H/2}}{\sqrt{(K - m\omega^2)^2 + (C\omega)^2}} \quad (8)$$

Where, F is the force acting on the structure, H is the maximum wave height, K is the Surge/Heave stiffness, M is the total mass of structure, C is the damping coefficient and ω is the Surge/Heave natural frequency.

1.5.2 Equation of motion

The motion equations for a floating body can be formulated based on Newton's second law. For an object with 6 degrees of freedom, this law can be expressed as [36] in Eq. (9),

$$\sum_{k=1}^{6} M_{jk}\ddot{\eta}_k = F_{jk} \quad (9)$$

1.6 Previous Studies

This section compiles several previous works that can serve as references for those interested in the structural design and performance metrics of offshore and floating photovoltaic (FPV) systems.

Wu *et al.,* [37] investigated fatigue characteristics in offshore structures, highlighting the importance of transition locations and the impact of tension and corrosion on moorings. Building on related aspects, Yeon *et al.,* [38] focused on wind load predictions on offshore structures by assessing velocity profiles and turbulence patterns, which are critical for accurate modelling and design. Similarly, Lee *et al.,* [39] developed a solver for simulating coupled platform-mooring system dynamics, aiming at improving accuracy and identifying operational challenges, further emphasizing the complex interactions in marine environments. Further, Choi *et al.,* [40] examined the aerodynamic impacts of wind on floating solar panel arrays to inform better support structure design, complementing the studies on offshore systems by integrating renewable energy considerations. This research aligns with the work of [2,11,41], who explored factors affecting floating solar farms' stability and performance, including mass distribution, environmental forces and climate change implications, thereby broadening the scope to environmental sustainability.

In parallel, [5,6,18,42-44] introduced novel concepts and analyses to improve FPV designs' resilience and performance in challenging conditions, suggesting a trend towards innovative adaptations in marine technology. Supporting this trend, Hong *et al.,* [45] and Cebada-Relea *et al.,* [12] investigated ways to minimize hydro elastic responses and fatigue damage in floating structures, focusing on longevity and durability. Additionally, Jia *et al.,* [46] analysed the impact of wind loads on offshore FPV systems, emphasizing the importance of array configuration, which is vital for optimizing performance and safety. Similarly, Du *et al.,* [47] analysed mooring systems for FPV arrays, demonstrating the superiority of the taut configuration in handling various tidal and environmental conditions, thereby providing practical solutions to enhance stability and efficiency in floating photovoltaic systems.

2. Methodology

This study proposes a floating design system and employs an Excel-based analytical model to investigate the hydrodynamic response of the system under various water conditions. The methodology, including the test matrix, is outlined in Table 1. Wave parameters are calculated using Airy Linear Wave Theory, while the wave forces acting on the structure are determined through the Morison equation. In these calculations, the floating system is treated as a rigid body subjected to regular waves.

Table 1
Hydrodynamic design parameters matrix

Water depth, d (m)	Wave height, H (m)	Wave period, T (m)	Water current, Uc (m/s)
5-70 m	2-10 m	1-10 s	0.9476 m/s

2.1 Model Description

The configuration of the tested model consists of 3 main platforms and 2 sidewalks, as illustrated in Figure 2. The PV panels will be mounted on the main platform and the sidewalks will act as ways for maintenance and other services. The floating system is designed with one-sided pneumatic support by increasing the depth of the short edge of the floats compared to the inner depth. The pneumatically supported floating structure has been proven to reduce hydrostatic responses [45].

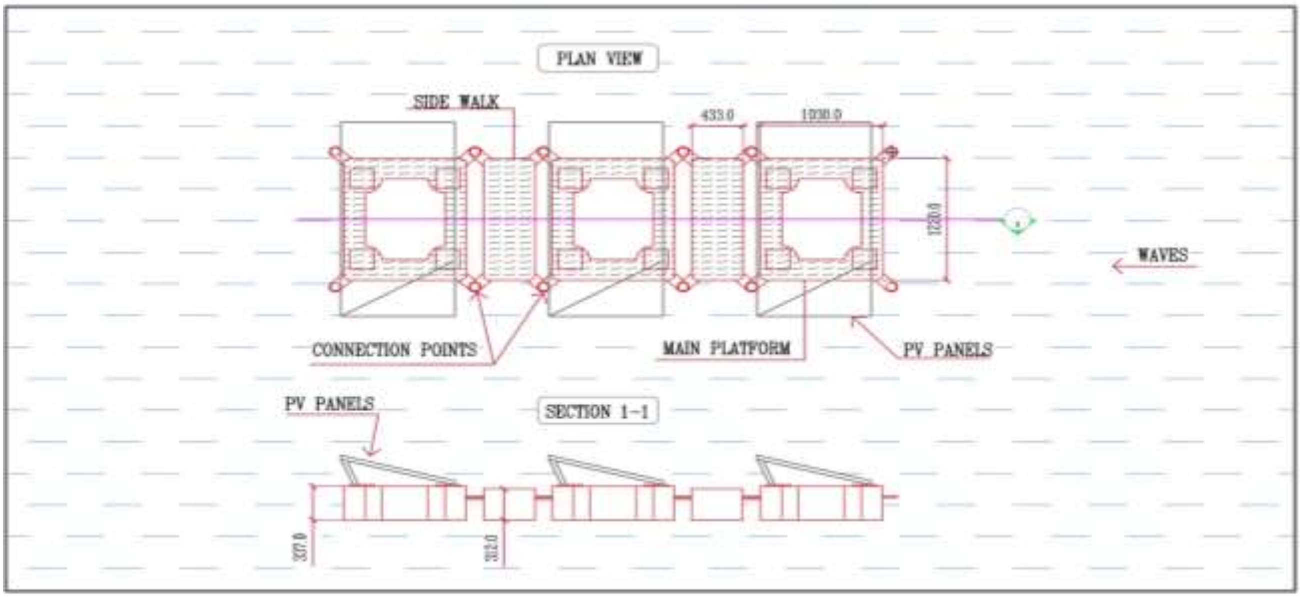

Fig. 2. Floating PV system model configuration

3. Results

This paper studies the RAOs for the proposed design of FPVs in different modes of motion: surge, heave and pitch, under various wave frequencies. The observed sea states are as shown in Table 1. It is important to note that the mooring system was not included in the applied model, introducing uncertainties regarding the higher RAO values. Despite this, the calculations provide valuable insights into how the proposed FPV design responds to variations in environmental conditions.

3.1 The Impact of Changes in Water Depth on RAOs

The RAOs for surge, heave and pitch movements were analysed under varying water depths under a constant wave height equals to *4m*. The variations in RAO surge curves are observed within the frequency range of *0.1–0.25 1/s*, as shown in Figure 3. The first observation is that the highest RAO surge was recorded at a water depth of *5m* and the responses decreased with increasing water depth. However, within this frequency range, the variations in RAO surge curves became negligible once the water depth exceeded *40m*. For higher frequencies, above *0.25 1/s*, the RAO surge curves indicate a negligible impact of water depth on the response of the FPVs. Additionally, the RAO surge tends to decrease higher frequency indicating that the surge motion is more pronounced to the longer wave periods.

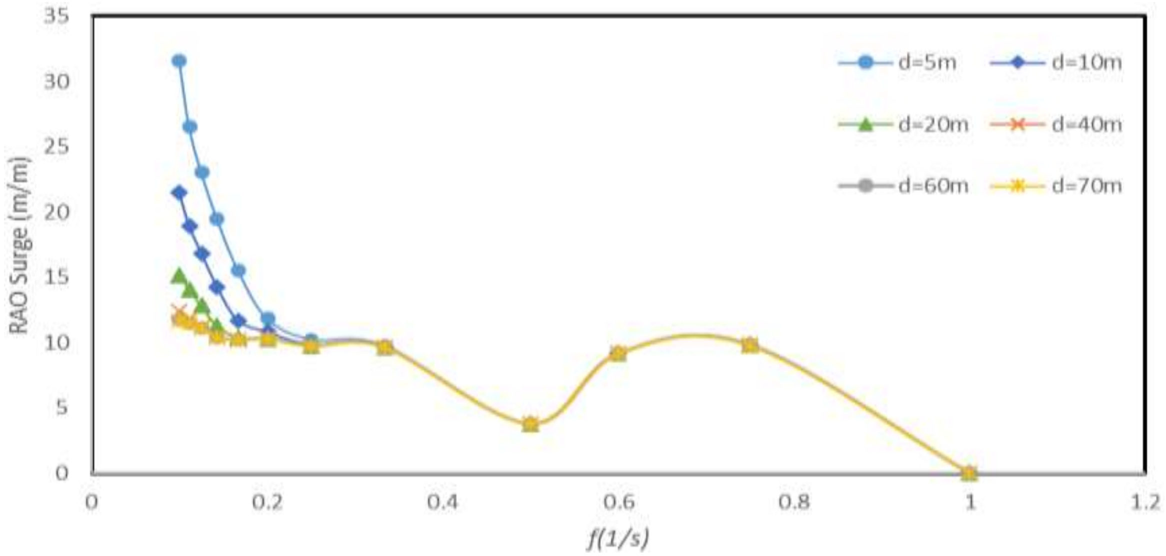

Fig. 3. Variation of surge RAOs with water depth, at H = 4m

Figure 4 shows that the RAO heave remains relatively consistent across all observed water depths, indicating a negligible influence of water depth on heave motions. However, the maximum RAO heave values are observed at higher frequencies, suggesting that heave motions are more sensitive to shorter wave periods.

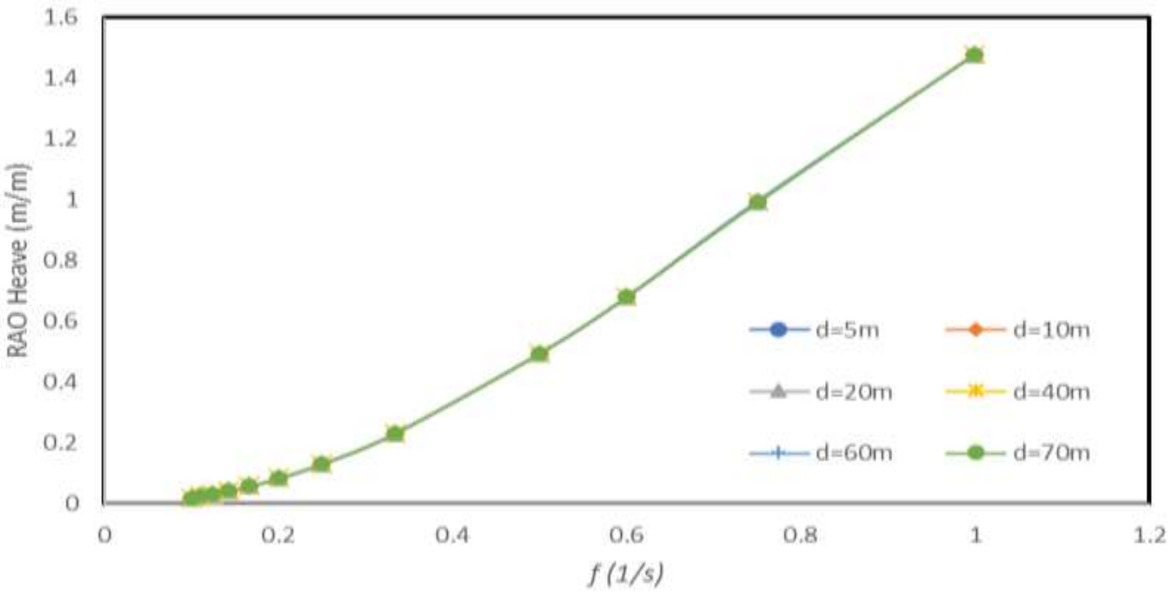

Fig. 4. Variation of Heave RAOs with water depth, at H = 4m

Closer observations were recorded for the RAO pitch regarding the impact of water depth, as illustrated in Figure 5. The pitch RAOs exhibit minimal variation with changes in water depth. In contrast to RAO heave, the maximum RAO pitch is observed at low frequencies, indicating that pitch motions are more pronounced with longer wave periods. The negligible effect of water depth on heave and pitch motions implies that FPV systems can maintain stability across different depths, making them versatile for various marine environments.

Overall, this consistency across depths suggests that variations in water depth do not have a significant impact on the responses of the hydrodynamic system. This observation aligns with a reference that claims FPVs is less sensitive to changes in water depth [48].

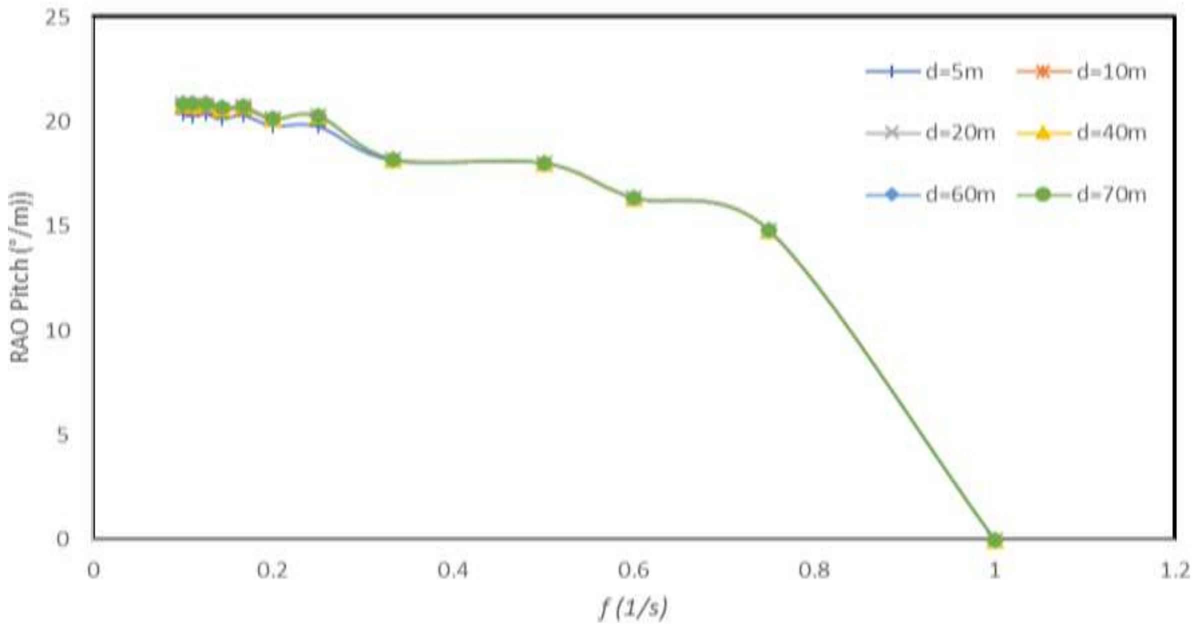

Fig. 5. Variation of pitch RAO with water depth, at *H* = 4m

3.2 The Impact of the Change in Wave Height

The effect of the variation of wave height has been studied at *H* = 2, 4, 6, 8 and *10m* for surge, heave and pitch responses under a constant water depth equals to *70m*. The first observation is that the RAO surge is directly proportional to the wave height. As shown in Figure 6, the highest RAO surge is recorded at *H = 10m*, while the lowest is at *H = 2m*. This direct proportionality indicates that larger waves induce greater surge motions, which must be considered in the design to ensure structural stability under high wave conditions.

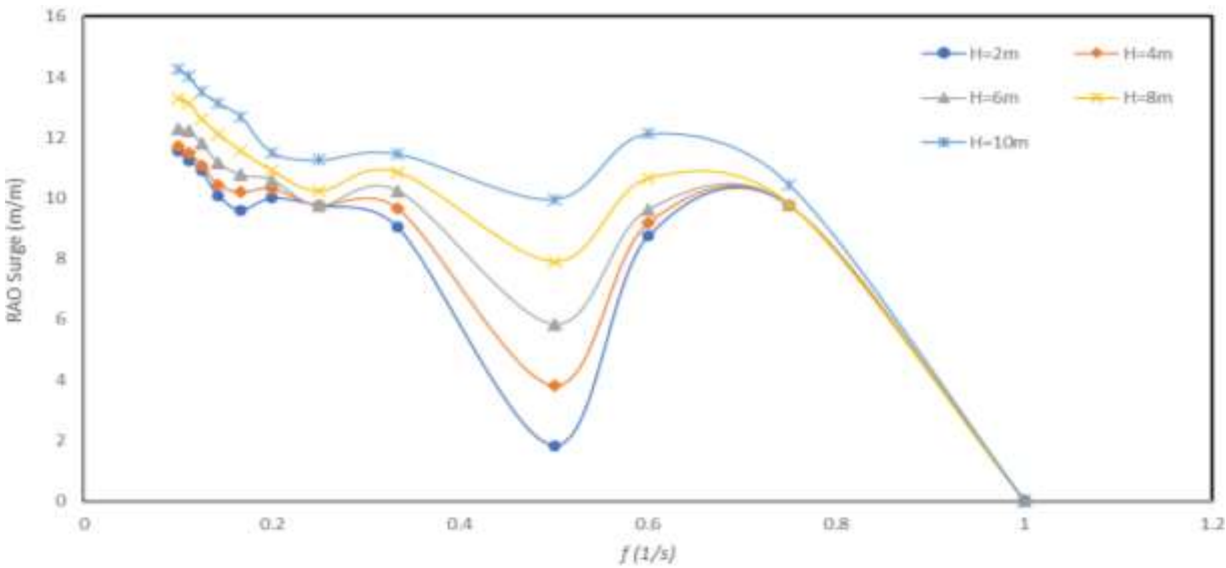

Fig. 6. Variation of surge RAO with wave height at *d* = 70m

Similarly, for heave movement, the highest RAO values are observed at *H = 10m*, as depicted in Figure 7. However, the variations in heave responses are relatively small compared to the surge responses, suggesting that heave movement is less sensitive to changes in wave height.

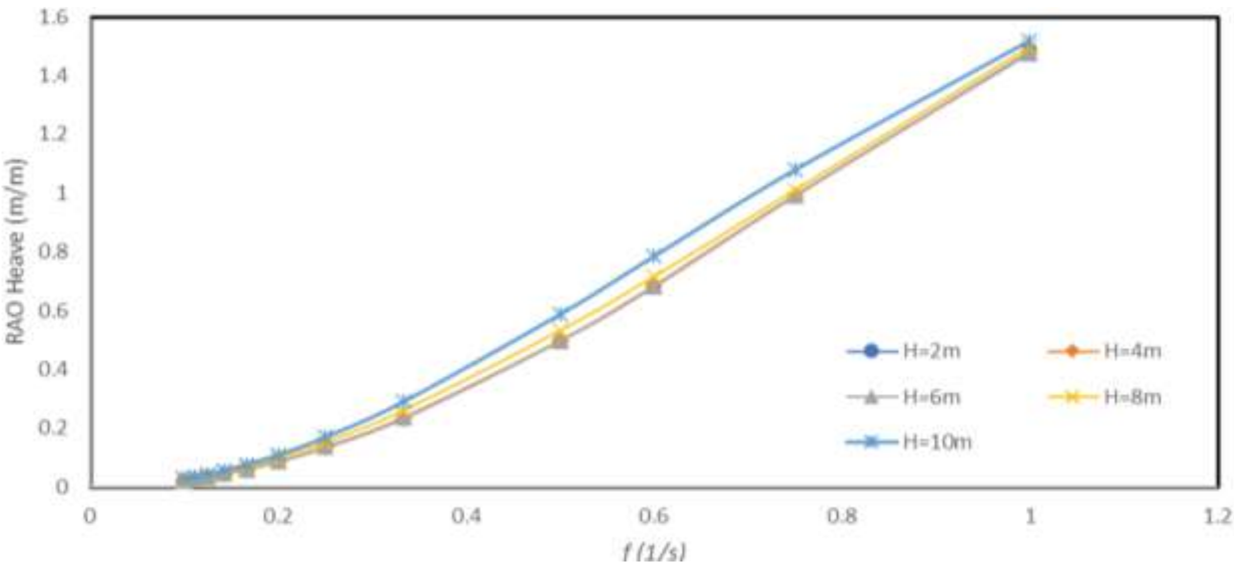

Fig. 7. Variation of heave RAO with wave height at *d* = 70m

For pitch movement, the maximum RAO is also observed at H = 10m, demonstrating a direct relationship with wave height as illustrated in Figure 8. The proportional increase in pitch RAOs with wave height highlights the importance of considering wave-induced rotations in the design of FPV systems.

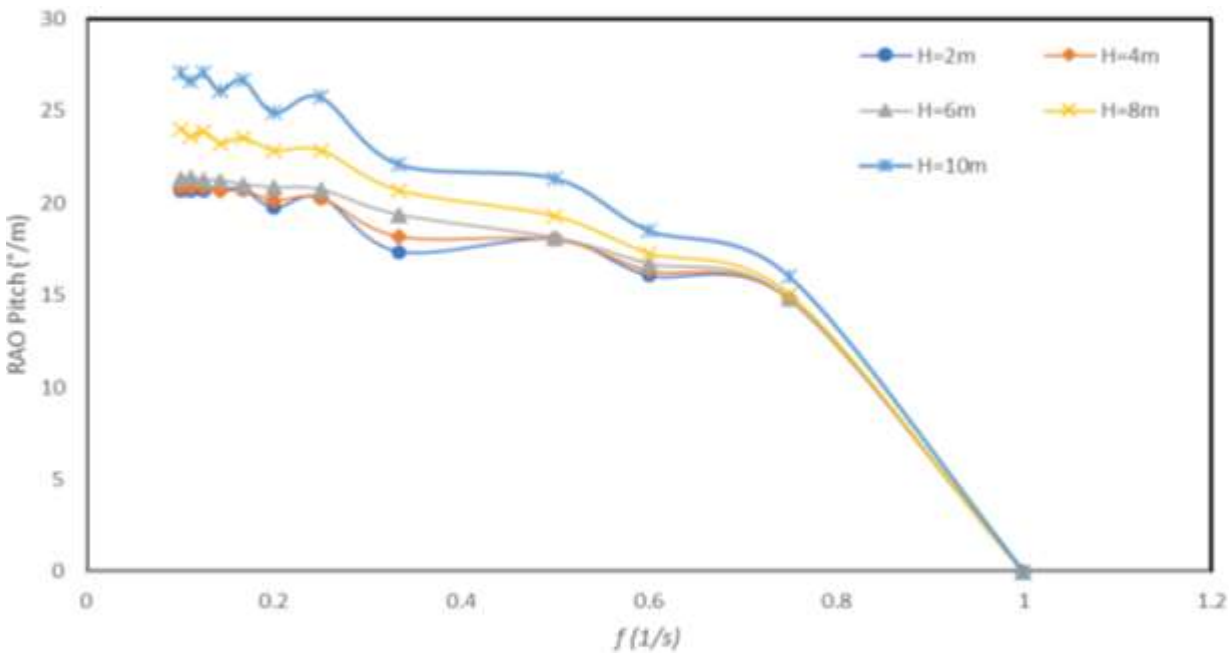

Fig. 8. Variation of pitch RAO with wave height at *d* = 70m

Overall, the results show that the impact of variation in wave height is more pronounced compared to that of water depth. The findings clearly indicate a direct relationship between an increase in wave height and the response of the FPVs in surge, heave and pitch modes. This observation aligns with literature suggesting that FPVs responses are highly sensitive to changes in wave height [48].

4. Conclusion

In conclusion, this study represents a significant contribution to the field of renewable energy by deepening our understanding of the hydrodynamic behaviours of Floating Photovoltaic Systems (FPVs) in its response to varying environmental conditions. This work has elucidated the distinct impacts of water depth and wave height on the surge, heave and pitch responses of FPVs. Specifically, it has been discovered that water depth predominantly influences the surge movement, while wave height correlates strongly with all hydrodynamic responses. Furthermore, the surge and pitch responses are observed to be higher at lower frequency levels, in contrast to the heave movement, which behaves differently.

These findings pave the way for more tailored and efficient FPV designs that can better withstand the challenges posed by offshore environments. Looking ahead, the tested design in the paper will be experimentally studied in real-world conditions to further solidify the reliability and performance of the design.

Acknowledgements
The authors would like to acknowledge the continued support by Universiti Teknologi PETRONAS (UTP) and the financial support provided by GR&T, grant number (015MD0-123).

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