

Enhancing Pure Oscillatory Response Motion Performance: Innovative Designs for Semi-Submersible and Catamaran Floating Photovoltaic Systems (FPVs) in Various Sea-State Conditions

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Abstract—A study approach to the novel design of floating photovoltaic systems has been provided using CFD simulation to determine motion characteristics on irregular waves with the JONSWAP spectrum under various water conditions. The simulation included in the frequency domain, shows that the CFPV model exhibits more stable behavior compared to its alternative model. This is due to the findings that the SFPV model has motion excitation associated with its own RAO against the wave energy spectrum at a frequency of 2.13 rad/sec (SS-2). This leads to a significantly dominant difference in motion quality concerning the significant response motion parameter. The quality difference values can be distinguished as heave with a value of 0.26 meters, roll with a value of 4.19°, and pitch with a value of 1.27°.

Keywords — *CFD, CFPV, Renewable Energy, Seakeeping characteristics, SFPV.*

I. INTRODUCTION

ASEAN has set an ambitious target of achieving a 35% share of renewable energy (RE) in its total installed power capacity by 2025 [1]. In addition, each member state has decided on its ambitious objectives for adopting renewable energy and reducing carbon emissions. Floating Photovoltaic (FPV) technology presents significant promise in supporting these nations in achieving their energy security objectives and renewable energy goals. FPV systems are especially beneficial for countries that have abundant solar resources. These systems offer a practical solution to the issue of limited land availability

and enable greater production of renewable energy without choosing deforestation, which leads to the extinction of birds due to habitat loss, erosion, runoff, and changes in microclimate [2]. In the ASEAN region, the annual levels of Global Horizontal Irradiance (GHI) are constantly high, with most locations experiencing GHI values over 1900 kWh/m². Figure 1 shows that the GHI values in Northern Vietnam are currently at their minimum, measuring approximately 1100 kWh/m². Conversely, the southern part of Indonesia (Timor Leste) demonstrates the most elevated levels of GHI, surpassing 2100 kWh/m².

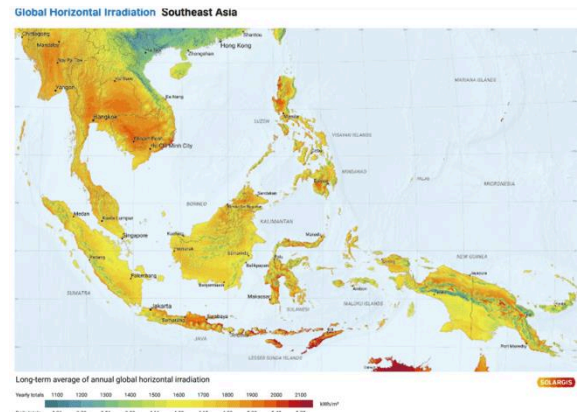


Figure 1. Global Horizontal Irradiation in Southeast Asia [3]

Various technical assessments have been performed on FPV technology in countries such as China [4], Korea [5], France [6] Indonesia [7], [8] and Singapore [9]. This technical review is specifically concerned with the use of FPV technology in waterbody areas, such as natural and artificial reservoirs and ponds used for irrigation purposes. The implementation in waterbody areas is typically expected to address situations where the dam's energy generation is insufficient. In such cases, solar power can be employed to supplement the energy need. Reference [10] conducted a thorough assessment of the implementation of FPV technology in a hydroelectric plant in Brazil. The findings indicate the prediction that the implementation of both power-generating technologies could alleviate energy curtailment during periods of peak demand.

Furthermore, the efficiency of FPV technology can be improved when used in near-shore areas because it allows for greater access to ocean space, which has a larger technical area compared to the limited surface area of water dams. In Indonesia, for example, regulations from the Public Work and Housing Department [11] restrict the installation of FPV systems only to 5% of the total dam area.

When designing a FPV system, a crucial aspect to consider is the floating structural component. It has a vital role in ensuring the system's buoyancy and stability. Reference [12] explained that the floating structure is often constructed using non-hazardous, UV light-resistant, and maintenance-free plastic materials that are known for their strong tensile strength, such as High-Density Polyethylene (HDPE).

Therefore, this study involves a couple of innovative designs that incorporate the concept of multi-hull and semi-submersible configuration with HDPE material properties to obtain the motion quality characteristics in Indonesian water, as indicated by the sea-state condition. The research will investigate the influence of the initial design parameter, both of the proposed designs using Computational Fluid Dynamics (CFD) simulations.

II. PROBLEM APPROACH

A single structure with a service deck area capable of accommodating one mono-crystalline solar panel within 2.38 meters in length and 1.30 meters in width as well as capable of generating 665 Wp of electricity and it complies with the specifications provided by CSI Solar Co. Ltd [13] for both types of floating photovoltaic (FPV) system designs.

The primary oscillatory motions in regular waves, such as heave, rolling, and pitching, will be determined by analyzing the free-floating state for all proposed design models. The results will be demonstrated in a graph of Response Amplitude Operators (RAOs), with the frequency domain shown on the horizontal axis (X-axis) and the ratio of motion amplitude in a specific mode ($n = 3, 4, 5$) to the wave amplitude represented on the vertical axis (Y-axis).

A. 3-D Modelling and preliminary calculations

In this study, a visualization is provided for the suggested novel design of a floating structure services in FPV technology, as shown in Fig. 2 and Fig. 3.

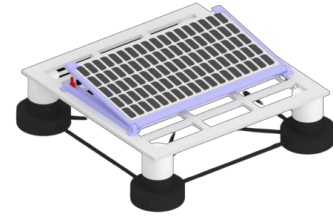


Figure 2. Semi-Submersible FPV

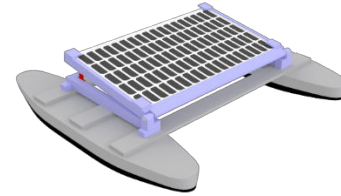


Figure 3. Catamaran FPV [14]

Furthermore, the main principle dimension for both design models is also shown in the Table 1 and Table 2.

Table 1. Main Principles Dimension of CFPV

Parameter	CFPV	Units
Length over All (LoA)	3.24	m
Breadth (B)	3.54	m
Height (H)	0.30	m
Draft (T)	0.12	m
Demihull Width (B1)	0.74	m
Spacing (S)	2.80	m
Hydrostatic properties		
Displacement (Δ)	437.31	kg
Keel to buoyancy (KB)	0.06	m
Longitudinal Center of Buoyancy (LCB) from AP	1.62	m

Table 2. Main Principles Dimension of SFPV

Parameter	SFPV	Units
Length over All (LoA)	3.10	m
Breadth (B)	3.10	m
Height (H)	0.75	m
Draft (T)	0.38	m
Height of Main Cylinder	0.20	m
Diameter of Main Cylinder	0.70	m
Height of Secondary Cylinder	0.50	m
Diameter of Secondary Cylinder	0.40	m
Diameter of Bracing	0.05	m
Deck Thickness	0.05	m
Hydrostatic properties		
Displacement (Δ)	437.31	kg
Keel to buoyancy (KB)	0,14	m
Longitudinal Center of Buoyancy (LCB) from AP	1,12	m

B. Governing Fluid Equation

The governing equation of the AQWA-CFD simulation software assumes that the fluid around the floating object is ideal. The ideal fluid is characterized by being homogenous, inviscid, irrotational, and incompressible. The numerical calculation of Response Amplitude Operators (RAOs) using the Boundary Element Method (BEM) techniques was conducted as described in ANSYS AQWA [15]. The potential velocity is represented by equation (1), where the unit vectors along the x-, y-, and z-axes are denoted by i, j, and k, respectively.

$$V = \nabla \phi = \frac{\partial \phi}{\partial x} i + \frac{\partial \phi}{\partial y} j + \frac{\partial \phi}{\partial z} k \quad (1)$$

Assuming that the fluid is incompressible, meaning that the mass of the fluid moving through and out of a control surface remains constant, then the Laplace equation can be expressed as follows.

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (2)$$

The incident waves affect the potential component (ϕ) that depends on the isolated space dependent. This potential can be divided into three parts: the potential from the incidence wave (ϕ_i), the potential from the radiation wave (ϕ_r), and the potential from the diffraction wave (ϕ_d). In addition, pressure is obtained by applying the Bernoulli equation, and the potential function is given by the following equation.

$$p = -\rho g z - \rho \left(\frac{\partial \phi_i}{\partial t} + \frac{\partial \phi_r}{\partial t} + \frac{\partial \phi_d}{\partial t} \right) \quad (3)$$

Subsequently, The equation (4) is used to determine the motion RAO. This equation is crucial for calculating the Response Amplitude Operator (RAO) associated with the motion of a floating object in a system.

$$\sum_{j=1}^6 [-\omega^2 (M_{ij} + M_{ij}^{ad}) + i\omega B_{ij} + C_{ij}] \eta_j^{A(1)} = \iint_S i\rho\omega (\phi_i^{(1)} + \phi_d^{(1)}) n_i' dS \quad (4)$$

The variables in the equation are defined as follows: M_{ij} represents the mass matrix of the FPV, M_{ij}^{ad} represents the additional mass matrix of the FPV, B_{ij} represents the radiation damping coefficient, C_{ij} represents the hydrostatic stiffness coefficient, η_j represents the amplitude FPV motion in the j^{th} mode motion, and n_i' represents the unit normal pointing outward from the surface of the FPV structure.

Furthermore, the JONSWAP ($\gamma = 2.5$) spectral wave theory was selected for its appropriateness in Indonesia's water. The JONSWAP spectrum formulation is an adaptation of the PM spectrum that includes additional parameters to account for the specific properties of ocean waves.

$$S_j(\omega) = A_\gamma S_{PM}(\omega) \gamma^{\exp\left[-0.5\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right]} \quad (5)$$

$$S_{PM}(\omega) = \frac{5}{16} \cdot H_s^2 \omega_p^4 \cdot \omega^{-5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right] \quad (6)$$

$$A_\gamma = 1 - 0.287 \ln(\gamma) \quad (7)$$

$$\sigma = 0.07 \text{ for } \omega \leq \omega_p \text{ or } \sigma = 0.09 \text{ for } \omega > \omega_p \quad (8)$$

The variables in the equation are defined as follows: $S_j(\omega)$ represents the JONSWAP spectrum, $S_{PM}(\omega)$ represents the Pierson-Moskowitz spectrum, ω_p represents the angular spectral peak frequency, T_p represents the spectral peak period, H_s represents the significant wave height, A_γ represents the normalizing factor, γ represents the non-dimensional peak shape parameter, and σ represents the spectral width parameter.

In addition, the behaviour of FPV in irregular waves can be determined by comparing the RAOs with the wave spectrum, which converts wave energy into response energy using equation (11).

$$S_{\zeta r}(\omega) = RAO^2 \times S_\zeta(\omega) \quad (9)$$

$$\zeta_s = 2\sqrt{m_0} \quad (10)$$

$$m_0 = \int_0^\infty S_\zeta(\omega) d\omega \quad (11)$$

The variables in question are $S_{\zeta r}(\omega)$, which represents the response spectrum, $S_\zeta(\omega)$, which represents the wave spectrum, and m_0 , which represents the area under the curve of the response spectrum.

III. CFD NUMERICAL SETUP

In AQWA, the mass attribute is referred to as a "point mass" where the mass is automatically calculated and only the radius of rotation is manually input using the floating object shape discretization method, as displayed in Table 4. Subsequently, a fine mesh is employed to determine the boundary between the wet and dry surfaces of the FPV as illustrated in Figure 6

Table 3. Radii of Gyration

Component	CFPV (m)	SFPV (m)
K _{xx} (X-Axis)	1.15	1.02
K _{yy} (Y-Axis)	0.68	0.94
K _{zz} (Z-Axis)	1.33	1.33

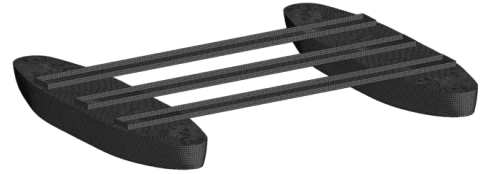


Figure 4. Mesh Visualization of CFPV [14]

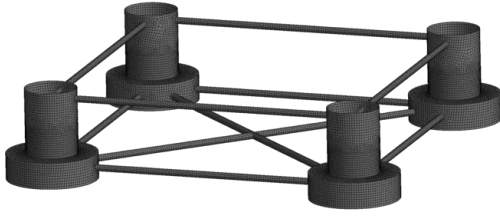


Figure 5. Mesh Visualization of SFPV

IV. RESULT AND DISCUSSION

This section presents the findings of seakeeping numerical simulations for all designs. The wave heading is only taken into account at three specific angles, which are $\phi = 0^\circ$ (following sea), $\phi = 45^\circ$ (quartering sea), and $\phi = 90^\circ$ (beam sea), due to the symmetrical geometry in the stern and bow both of CFPV and SFPV structures. In addition, 2D surface graphs are presented to illustrate the different motion characteristics of the semi-submersible and the catamaran. Unfilled space with white colour indicates no difference in motion quality between the two models. Whereas the red areas show that the semi-submersible experiences greater intensity in its excitation motion than the catamaran model.

A. Heave Mode

For the heave motion mode, it has been observed that under the sea-state 1 condition, no significant difference exists between the two models. However, under sea-state 2 conditions, a notable difference has been recorded, with a disparity reaching up to 0.26 meters between the catamaran model and the semi-submersible model. The difference is attributed to the peak energy of the irregular waves at this condition, which occurs at a frequency of 2.13 rad/sec. According to the RAO graph, the semi-submersible model is shown to exhibit a more dominant response compared to the catamaran model at this frequency. Whereas, for sea-state conditions 3 and 4, a decrease correlates with values shown in the RAO.

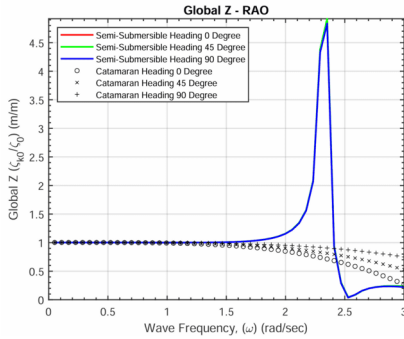


Figure 6. Heave RAO

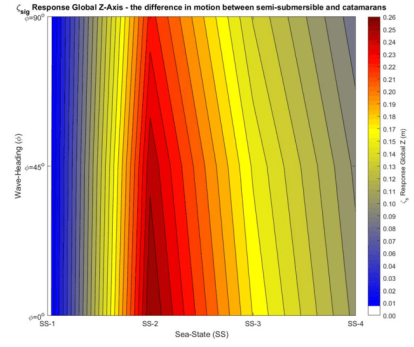


Figure 7. Difference Motion of both proposed design (Heave)

B. Roll Mode

Furthermore, in the roll motion mode, it is indicated that significant differences in motion occur at a wave heading of $\phi = 90^\circ$ (beam sea) as the dominant direction of movement [16]. This is also influenced by the interaction between the peak energy of the wave spectra and the peak RAO value for the semi-submersible, with a total motion difference exceeding 4.19° at a frequency of 2.13 rad/sec. The graph also demonstrates that as the depth increases, the magnitude of the motion difference decreases.

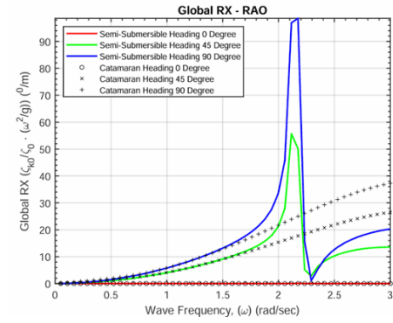


Figure 8. Roll RAO

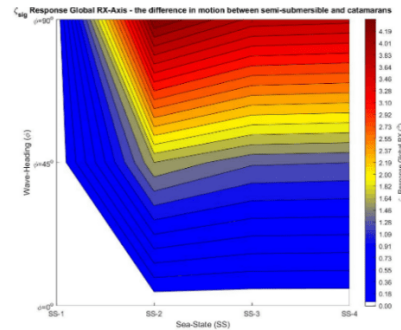


Figure 9. Difference Motion of both proposed design (Roll)

C. Pitch Mode

The final motion mode is pitch, which is the inverse of the roll motion mode. An interesting observation is illustrated in the 2D surface graph below, showing that at wave headings of $\phi = 90^\circ$ (beam sea) and $\phi = 45^\circ$ (quartering sea), no differences are

observed between the two models for any sea-state condition. However, at wave heading of $\phi = 0^\circ$ (following sea), a significant difference is noted due to the interaction at the structure's natural frequency, as indicated by the rise in the RAO curve in this dominant direction. This difference reaches up to 1.27° .

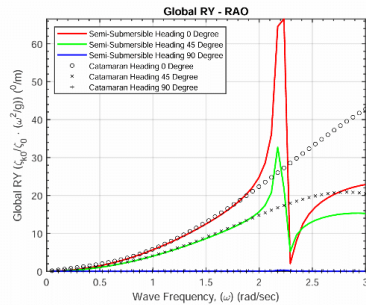


Figure 10. Pitch RAO

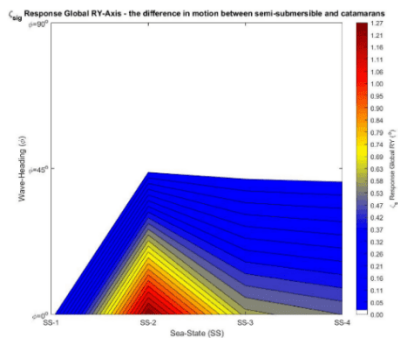


Figure 11. Difference Motion of both proposed design (Pitch)

V. CONCLUSION

An investigation has been done to examine the effect of different 3D basic model floating platforms and environmental conditions on the performance of FPV systems. A numerical of CFD simulations was executed to analyze the pure oscillatory motions in heave, pitch, and roll for all proposed designs, using 3-D diffraction as an approach. The stochastic method demonstrates that the CFPV structure displayed better motion performance in comparison to its alternative model, which is characterized by lower values on its RAO graph and significant response structure (ζ_{sr}).

ACKNOWLEDGMENT

The authors express their gratitude to the Institut Teknologi Sepuluh Nopember for providing financial support for the study project through the "ITS Center Collaboration Research Scheme" under contract number: 1322/PKS/ITS/2024. The authors express their gratitude for the facilities and the scientific and technical assistance provided by the Hydrodynamics Laboratory of Naval Architecture.

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2024-10-21

IEEE

<https://doi.org/10.1109/icue63019.2024.10795525>

Dhaifullah MH, Jifaturrohman MI, Putranto T, et al., (2024) Enhancing pure oscillatory response motion performance: innovative designs for semi-submersible and catamaran floating photovoltaic systems (FPVs) in various sea-state conditions. In: 2024 International Conference on Sustainable Energy: Energy Transition and Net-Zero Climate Future (ICUE), 21-23 October 2024, Pattaya City, Thailand