Comparative Study of Effect of Wind and Wave Load on Floating PV: Computational Simulation and Design Method

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ABSTRACT

Interest in renewable energy is rapidly growing around the world. One of the most popular renewable energy sources is solar power, and photovoltaic (PV) systems are the most representative route for generating solar energy. However, with the growing adoption of solar power systems, the demand for land on which to install these systems has increased, which has caused environmental degradation. Recently, floating PV systems have been designed to utilize idle water surface areas of dams, rivers, and oceans. Because floating PV systems will be exposed to harsh environmental stresses, the safety of such systems should be secured before installation. In this study, the structural robustness of a floating PV system was analyzed by conducting numerical simulation to investigate whether the system can withstand harsh environmental stresses, such as wind and wave loads. Additionally, conventional wind and wave load predictions based on the design method and the simulation results were compared. The comparison revealed that the design method overestimated wind and wave loads. The total drag of the PV system was significantly overestimated by the conventional design criteria, which would increase the cost of the mooring system. The simulation offers additional advantages in terms of identifying the robustness of the floating PV system because it considers real-world environmental factors.

Keywords: Floating PV (수상 태양광 발전 부유체), Computational Analysis (전산 해석), Design Method (설계적 방법), Wind Load (풍하중), Wave Load (파랑하중)

1. Introduction

As interest in renewable energy increases rapidly worldwide, solar energy has emerged as one of the primary sources of renewable energy owing to its sustainability and ubiquity. Photovoltaic (PV) systems are the most common means for collecting and using solar energy\(^1\). The global PV market has grown at
an annual rate of more than 50 percent over the past decade, and this growth has mostly been driven by
government support for renewable energy\(^2\).

As solar power generation grows, the negative
environmental impacts of solar energy systems have
come to the fore. Large solar power installations raise
concerns about land degradation, deforestation, and
habitat loss. Although the total land area requirements
vary depending on the technology, a typical PV
system requires 3.5 – 10 acres of land to generate one
megawatt of power. The growth of solar power
generation has paradoxically increased deforestation.
Moreover, unlike wind facilities, the land on which
solar power systems are installed can rarely be used
for agricultural purposes at the same time. Therefore,
new solar power generation systems that have the
least impact on the environment are needed.

Floating PV systems were introduced to utilize idle
water surface areas of dams, rivers, and oceans (Fig.
1). When a solar system is installed on water, it
reduces the amount of sunlight that passes
underwater, thus preventing the growth of green algae
and reducing the evaporation of water. Floating PV
systems are installed on idle water surfaces, which
means they do not take up agricultural or forest land,
thus helping prevent land degradation or
deforestation\(^3-5\). However, the structural robustness of
floating PV systems under harsh environmental
stresses has not been widely investigated, and there
are no comprehensive guidelines to guarantee the
structural safety of floating PV systems.

In this study, the structural robustness of a floating
PV system is analyzed by conducting a numerical
simulation to investigate whether the floating PV
system can withstand harsh environmental stresses
from wind and wave loads. Additionally, wind and
wave load predictions made using conventional design
methods are compared with results of the simulation.

2. Relevant Equations

2.1 Reynolds-Averaged Navier-Stokes (RANS) equation

Flow velocity and pressure on the PV system are
simulated using the RANS equation. The RANS
equation, represented by the continuity equation and
momentum equation, is expressed as follows\(^6\):

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0
\]  

\[
\frac{\partial u_j}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_i} = -\frac{1}{\rho} \frac{\partial P}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} + f_j
\]

where \(\rho\) denotes the density of fluid, \(u\) the flow
velocity, \(P\) the pressure, \(\nu\) the kinematic viscosity,
and \(f\) the external force.

2.2 Potential theory of hydrodynamic

diffraction

The behavior and pressure of an object are
calculated using the potential theory. The governing
Laplace equation for the potential function can be
written as follows\(^6\):

\[
\nabla^2 \varphi = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0
\]

\[
\varphi = \sum_{j=1}^{6} \varphi_j + \varphi_n + \varphi_d
\]

where \(\varphi\) is potential function, \(\varphi_j\) the radiation
potential composed of 6 components corresponding to

Fig. 1 Conceptual diagram of floating PV
due to motions in the six directions, \( \varphi_w \), the incident potential, and \( \varphi_d \), the diffraction potential generated by incident waves.

### 2.3 Drag and lift coefficients

The drag coefficient is defined as follows:

\[
C_D = \frac{F_D}{\frac{1}{2} \rho u^2 A_p}
\]

(5)

The lift coefficient is defined as follows:

\[
C_L = \frac{F_L}{\frac{1}{2} \rho u^2 A_S}
\]

(6)

where \( \rho \) is the mass density of fluid, \( u \) the fluid velocity, and \( F_D \) and \( F_L \) the drag and lift forces, respectively. \( A_p \) and \( A_S \) are the frontal projection area and surface area, respectively.

### 2.4 Design method for wind load analysis

The wind pressure load is conventionally calculated according using harbor and fishery design criteria as follows:\(^7\):

\[
P_w = \frac{1}{2} \rho_A C_D U_w^2
\]

(7)

where \( \rho_A \) denotes density of air, \( C_D \) the drag coefficient of the floating PV, \( U_w \) the wind velocity, and \( P_w \) the pressure that, by definition, acts on the floating PV system because of wind. In this study, we set \( T = 3.22 \) s, \( \rho_{WA} \) as 1030 kg/m\(^3\), \( g \) as 9.81 m/s\(^2\), \( d \) as 0.085 m, \( H_{\text{max}} \) as 0.1 m and 0.65 m, \( L \) as 16.2 m, \( \theta \) as -15 degrees are used. The resultant \( P_1 \) was 1003.18 Pa and 6520.70 Pa, \( P_2 \) was 859 Pa, \( P_3 \) was 997.17 Pa and 6481.58 Pa, \( \alpha_1 \) was 1.01, and \( \alpha_5 \) was 0.99.

### 3. Numerical Simulation

#### 3.1 Design of floating PV

A floating PV system is composed of panels, floaters, joints, and brackets among other components, as shown in Figs. 2 and 3. The angle between the panels and the ground is 6°, and the entire system used in this study is in the form of a 4 \( \times \) 4 array. In addition, the shape of the floating PV is simplified in the analysis process to facilitate convergence and increase efficiency.

#### 3.2 Computational fluid dynamics (CFD) setup and conditions

To analyze wind load, we used ANSYS Fluent (ANSYS, Inc., PA, USA). We used the \( k-\omega \) shear stress transport (SST) model is used as a turbulence model. The incompressible RANS equations were solved using the SIMPLE algorithm. The convective
terms were discretized with a second-order accurate upwind scheme. The flow field was divided into four cases in which the wind direction was considered as 0° and 45° from the front and the back. As shown in Fig. 4, the inlet condition was applied with a uniform flow velocity of 45 m/s, and the outlet condition was set to atmospheric pressure. No-slip conditions were applied to the bottom floor and the floating PV surfaces, and slip wall conditions were applied to the rest of the walls. The fluid domain was discretized with a growth rate of 20%, local size of 50 mm on the floating PV size, and global size of 100 mm. A total of 18 million tetrahedral cells per case were used in the CFD simulations (Fig. 5).

### 3.3 AQWA set up and conditions

ANSYS AQWA (ANSYS, Inc., PA, USA) is used for wave analysis. As shown in Figure 6, the wave pressure analysis was performed using hydrodynamic diffraction for all periods, wave heights, and wavelengths. The period was 3.22 s, and the corresponding wavelength was 16.2 m. The wave height was 0.2 m and 1.3 m, and the structural...
properties of each member, as summarized in Table 1, were applied. Hydrodynamic diffraction can only be used to calculate the force acting on the surface, and the internal members must be removed. Because the number of meshes was limited to a maximum of 40,000, the surface mesh used in the simulation conducted using AQWA was simplified as shown in Figure 7.

4. Results and Discussion

4.1 Frontward wind at 0°

Frontward wind generates a significantly larger lift force than drag force on the panels (Fig. 8). A pressure of up to 1 Pa, and a minimum pressure of −922 Pa, is generated by 0° frontward wind. Among the top panels, the maximum negative pressure acts on the panels in the front row, while smaller negative pressures act on the panels behind them. The bottom panels exhibit relatively uniform pressure distribution with a pressure of approximately −300 Pa. The wind velocity at the top of the first row is up to 56 m/s. A local low-velocity region due to recirculation flow can be observed around the edge of the first row of floating PV panels. The flow velocity decreases and stabilizes behind the second row.

4.2 Frontward wind at 45°

Maximum and minimum pressures of 230 Pa and −1237 Pa, respectively, are generated by 45° frontward wind (Fig. 9). In case of the top panels, the side and front edges of the PV assembly that directly encounter wind are acted upon by a large...
negative pressure. The magnitude of the negative pressure distribution acting on the bottom panels is approximately \(-300\) Pa, which is similar to that in case of 0° frontward wind.

The wind velocity reaches up to 55 m/s at the top of the first row of panels in the array, and the velocity distribution fluctuates and stabilizes owing to the effect of the angle.

4.3 Backward wind at 0°

Backward wind generates a significantly larger lift force than does frontward wind (Fig. 10). Maximum and minimum pressures of 1102 Pa and \(-1527\) Pa, respectively, are generated by 0° backward wind. In the top panel, the pressure is the highest in the rearmost row of ow panels. A positive pressure of up to 1102 Pa acts on the bottom panels, which tends to lift the panels. The wind velocity at the top of the first row is up to 59 m/s. A larger low-velocity region due to the recirculation flow is formed around the top panel in the rearmost row of the floating PV system. This low-velocity recirculation flow is main reason for low pressure on the top panel. Moreover, only the panels in the first row that encounter the backward wind are strongly affected, while the other panels are relatively weakly affected.

4.4 Backward wind at 45°

A pressure value of up to 1249 Pa and a minimum pressure of \(-2515\) Pa are generated by 45° backward
The lateral and longitudinal arrangement of the first panel shows the greatest negative pressure, and the distribution of negative pressure appears as a whole, and the back arrangement shows features that stabilize as the pressure becomes smaller and less. In case of the panel below, the greatest pressure is produced in the vertical arrangement of the first panel by wind direction, excluding the horizontal and vertical arrangement of the first panel, and showing features that stabilize as the pressure becomes smaller and less pressure is distributed in most cases. Velocity is shown to occur up to 61 m/s at the top of the first array of wind direction and to fluctuate and stabilize the velocity distribution with the effect of angles later.

### 4.5 Total drag and lift

Table 2 summarizes the drag and lift forces, drag coefficients, and lift coefficients at the top and bottom of each panel according to wind direction, and the highest drag coefficient of 1.296 is caused by the 0° backward wind. The maximum values of drag coefficients due to wind along other directions are relatively small overall.

Table 3 summarizes the drag and lift coefficients of the entire floating PV system according to wind direction. $C_{D, total}$ were 0.17, 0.18, 0.30, 0.24 and $C_{L, total}$ were 0.78, 0.63, 1.35, 0.96 at forward winds of 0 and 45 degrees, backward winds of 0 and 45 degrees, respectively. The results indicate that the entire system has smaller drag and lift coefficients than those predicted using the conventional design method.

### 4.6 AQWA

Figure 12 shows the wave pressure distribution due to 0.2 m and 1.3 m waves incident on the floating
Fig. 12 Result of pressure at 0.2 m and 1.3 m

Table 4 Comparison between AQWA and design method at wave height 0.2 m and 1.3 m

|       | 0.2 m      |                | 1.3 m      |                |
|-------|------------|----------------|------------|----------------|
|       | Max [Pa]   | Min [Pa]       | Max [Pa]   | Min [Pa]       |
| AQWA  | 1567.74    | -964.33        | 5475.11    | -6268.14       |
| Design method | 1856.17 | -997.17        | 7340.58    | -5622.58       |

Using the design method are different from those obtained in the CFD simulation are because the design method considered only the top of the frontward 0° panel whereas the CFD simulation considered both the top and bottom of the panel. In addition, the wind pressure calculated using the design method described in section 2.4 is 1870 Pa, and the maximum size of each wind direction is compared, except for that in case of the backward 0° wind. These differences are also thought to occur because only the top of the panel is considered, and the arrangement is not considered.

Table 4 compares the maximum and minimum pressure values obtained using AQWA with those obtained using the design method in cases of the 0.2 m and 1.3 m waves. In case of the 0.2 m wave, the maximum and minimum pressure values obtained using the design method are larger and smaller than those obtained using AQWA, respectively. In case of the 1.3 m wave, both the maximum and minimum pressure values obtained using the design method are greater than those obtained using AQWA. These differences are thought to arise from the fact that the design method does not consider the shape of the structure and the point at which the waves touch the floating PV system.

5. Conclusion

In this study, the structural robustness of a floating PV system was analyzed by conducting a numerical simulation and by using the conventional
design method. The following conclusions were drawn:

1. Wind direction was found to affect only the front array of panels encountering the flow. Backward wind resulted in higher pressure, drag, and lift than did forward wind.

2. A comparison of the total drag estimated using the conventional design method and the simulation revealed that the design method ($C_D = 1.5$) significantly overestimated the wind load acting on the floating PV system. Overestimation of the total drag would unnecessarily increase the cost of the mooring system.

3. In terms of wave load, the discrepancy between the design method and the numerical simulations was less than 20%. The maximum wave load occurred at the front and rear of the floating PV system, and the minimum wave load at the corners.

4. Although the conventional design method is simple and useful, the CFD simulation offers additional advantages in terms of identifying the robustness of the floating PV system because it considers real-world environmental factors, such as panel arrangement, wind direction, and shape of structure.

Acknowledgement

This research was supported by Ministry of Trade, Industry and Energy (MOTIE) and Korean Energy Technology Evaluation and Planning (KETEP; 2017-104-089)

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