Dynamic response of the mooring system in the floating photovoltaic power station

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Abstract—The floating photovoltaic power (FPV) station becomes popular to decrease carbon emission. However, limited research has been done on the dynamic response of the mooring lines of the FPV array. Based on a typical 2.14MW FPV array, this study investigates the displacement of the array and the mooring tension of the mooring lines. The numerical model of the FPV array is built through three-dimensional potential theory with 124 mooring lines. Firstly, the effect of the environment on the response is investigated under wave-only, current-only and wind-only conditions. Then, the tension and motion in the combined environmental loads are analyzed. It is found that the wind load has the greatest influence on the motion and mooring tension on the FPV power station, the effect of wave and current on the response is very limited.

1. Introduction

Due to the requirements of carbon emission and production of environment, many countries facilitate exploring alternative renewable energy to diversify energy sources, such as solar and wind energy. In 2020, the newly increased capacity of photovoltaic(PV) power stations in China reached 48.2GW.

Land-base PV power station needs a large area of land for construction, which is difficult to find useable land space with regards to vegetation protection, agricultural planning and urban development. A floating photovoltaic (FPV) power station on reservoirs, lakes and abandoned water bodies is a good alternative solution. FPV power station utilizes the useless water surface and enjoys the natural cooling effect from water evaporation.[1] The FPV system provides a cover on water surfaces and reduces water loss due to evaporation. [2]

Based on the 1MWp floating solar PV cell test-bed at Tengeh Reservoir in Singapore, Dai et al [3] analyzed the structural strength of floater, the comparison between numerical and experimental results showed that the finite element method(FEM) can provide well simulated displacement of the floater. Li et al [4] studied the hydrodynamic performance and wave loads of floater using 3D potential theory, the stress distribution of floater through FEM shows the high-density polyethylene(HDPE) meets the requirements of structural strength. Kim et al[5] introduced a type of FPV floater fabricated by fiber-reinforced polymer(FRP) and studied the mooring tension of FPV array according to relevant design code. Xiao et al[6] studied the wind load on the PV panels based on the experimental data from the wind tunnel test and simulation by computational fluids dynamics(CFD) as well as the wave loads by the potential theory. The study concluded the current and wave load of the FPV array is generally constant when the number of rows does not change. Some research on wave loads and structure strength about the FPV system has been done, but limited study on the mooring dynamic response of the FPV system. The mooring lines limit the maximum displacement of the FPV array and they are critical for the safe operation of the power station.

This study investigates the dynamic response of the FPV under wave, wind and current conditions. Firstly, a typical FPV array is selected as the study object and the numerical model of the FPV is developed using potential theory and dynamic model of mooring lines. Then, the mooring tension and displacement of the FPV under wave only, current only and wind only conditions are predicted. Finally, the dynamic responses are studied in the combined environment loads and the main loads on the FPV array are analyzed.

2. Numerical models

2.1. Model introduction

The main components of the FPV systems include floating modules, PV panels, mooring systems and inverters. Fig.1 shows the typical arrangement of the floating modules, which comprise a maintenance walkway for operation access and a PV panel floater for supporting PV panels in water. The floating modules are made of HDPE regarding their acceptable structure strength and durability in water bodies. The draft of the FPV system is generally designed to 30-60mm considering the floater modules provide large buoyance force and the weight of PV panels is light.

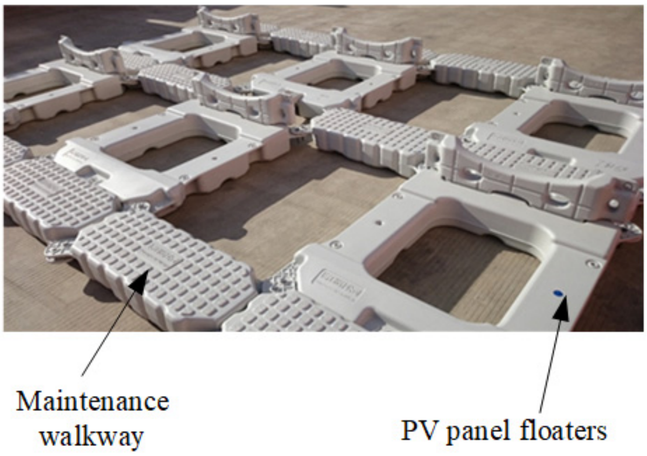


Fig.1 Typical floating modules for FPV system

The dynamic response of the mooring system is studied based on a typical 2.14MW FPV array shown in Fig.2. The array includes 84 rows and 56 columns of floating modules, 4704 PV panels and 124 mooring lines. The mooring lines manufactured by stainless steel wire ropes are designed as “V” type where two lines connect a shared anchor. The length of mooring lines is designed as 20m according to the average 10m depth of water bodies and variation of water levels in the service life of 25 years.

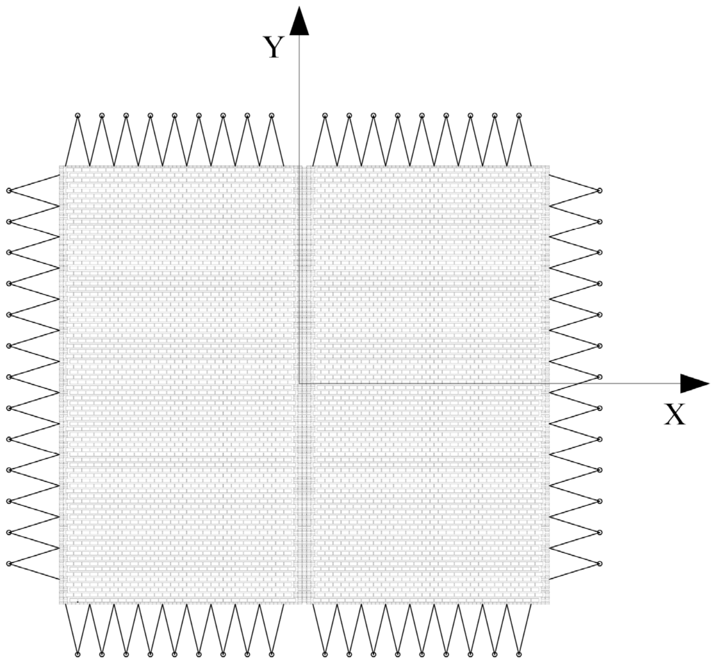


Fig.2 Mooring system of a typical 2.14MW FPV array

2.2. Environmental loads

The FPV system in water bodies suffers wave, current and wind loads. Since the water bodies inland are closed and small relative to the ocean, the wave is a secondary environment load for the FPV system. The wave loads on the FPV array are estimated through three-dimensional(3D) potential theory, which predicts the amplitude of radiation and diffraction force of the FPV system in the frequency domain. The geometry of the FPV array is complex and difficult for mesh generation, the numerical model is simplified to meet the requirements of mesh. The waterplane area of original and simplified modes keep the same. Fig.3 provides the simplified model of the FPV array and water pressure around the model at wave frequency 0.083Hz and wave amplitude 0.2m.

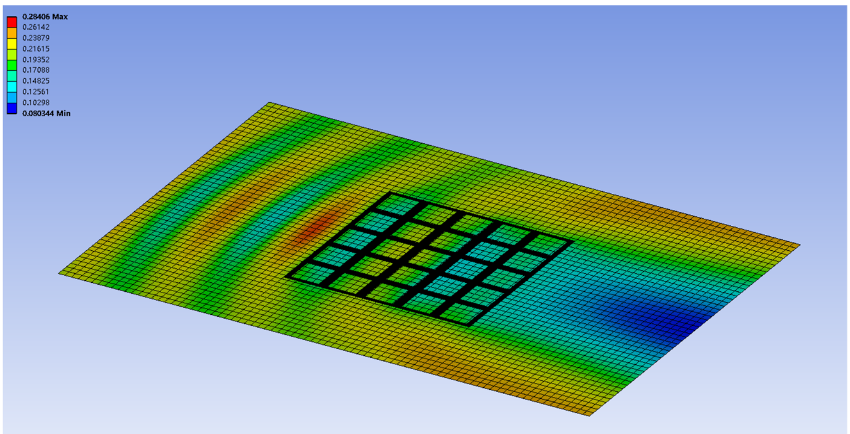


Fig.3 Water pressure by 3D potential theory

The wind and current loads are calculated as the following formula

$$F = \frac{1}{2} C_d \rho A v^2 \tag{1}$$

where F is wind or current load, C_d and ρ present drag coefficient and density of the fluid, A is the projected wind or current area, v means the velocity of wind or current. The environment parameters of each load case are given in Table.1. The regular waves are applied in the simulation and the wave period is constant. In Case 1~ Case3, the effect of wave, wind and current on the dynamic response of the FPV array and mooring tension is studied. In Case 4~ Case 6, the dynamic response in the combined environmental loads is analyzed. The direction of environmental loads is defined in the Y direction since the loads in this direction are the most dangerous.

Table.1 environment parameters of load cases

	Wave Height (m)	Wave period (s)	Wind velocity (m/s)	Current velocity (m/s)
Case 1	0.1~0.3	1.43	-	-
Case 2	-	-	14~26	-
Case 3	-	-	-	0.4~1.5
Case 4	0.2	1.43	20	1.5
Case 5	0.2	1.43	26	1.5
Case 6	0.3	1.43	26	1.5

2.3. Numerical Model for the Dynamic Analysis

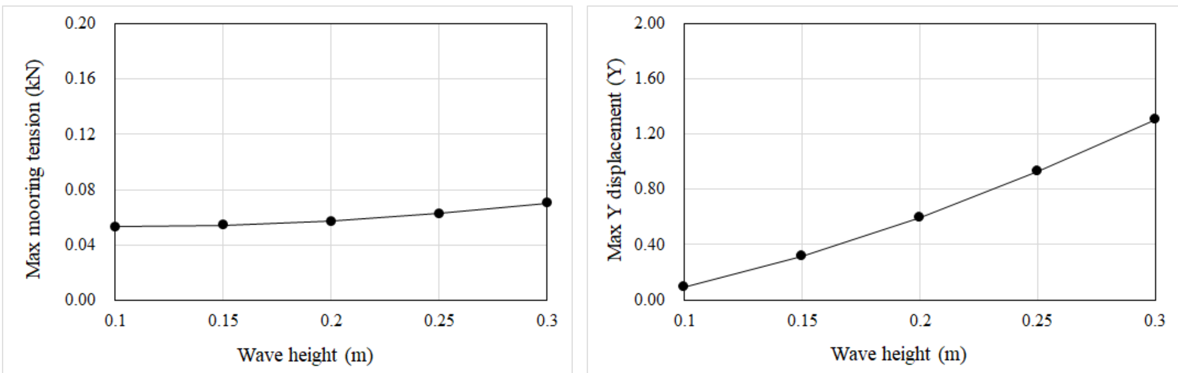
The dynamic analysis of an FPV array is performed according to the equation of dynamic motion as the following equation

$$M\{\ddot{x}\} + C\{\dot{x}\} + K\{x\} = \{F_B\} + \{F_R\} + \{F_G\} + \{F_M\} + \{F_H\} + \{F_W\} \tag{2}$$

where vector $\{\ddot{x}\}, \{\dot{x}\}, \{x\}$ present the acceleration, velocity and displacement of six degrees of freedom. M, C, K denote mass matrix, damping matrix and stiffness matrix, respectively. $\{F_B\}$ is buoyancy force; $\{F_G\}$ is gravitational force; $\{F_R\}$, $\{F_M\}$, $\{F_H\}$ *and* $\{F_W\}$ indicate restoring force, mooring loads, hydrodynamic force and wind load. Hydrodynamic force includes wave load and current load.

3. Results and Discussions

The dynamic displacement of the FPV array and mooring tension is analyzed based on the numerical model as described in Section 2. The mooring lines are simulated by a dynamic model since the catenary theory is not applicable for cases with tensioned mooring lines.

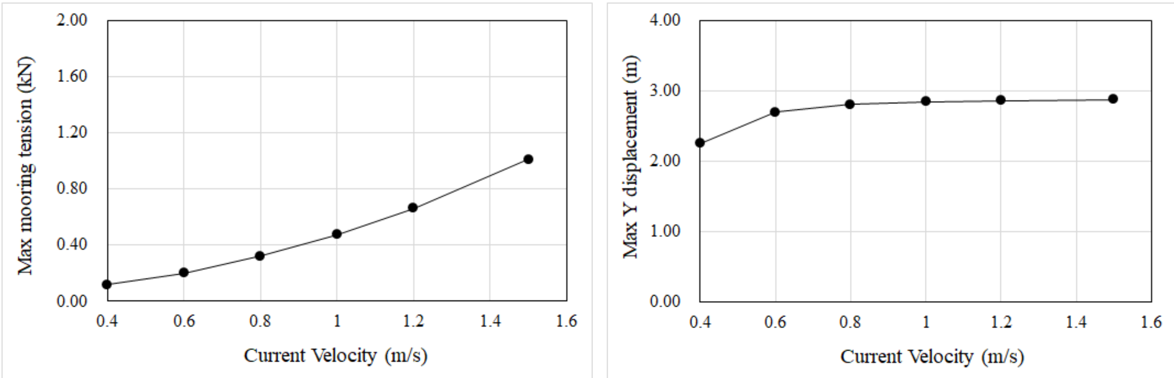


(a) Maximum mooring tension (b) Maximum displacement in Y direction

Fig.4 Dynamic response of the FPV array in Case1

Fig.4(a) presents the maximum dynamic mooring tension in all mooring lines in the wave-only condition (Case 1). The mooring tension increases slightly with the increment of wave heights. However, the maximum displacement of the FPV array increases significantly as shown in Fig.4(b). The wave heights in Case 1 are small and the motion of the FPV array less than the minimum displacement caused mooring lines tensioned. So, the mooring lines keep slack and mooring tension changes slightly during the motion in Case 1.

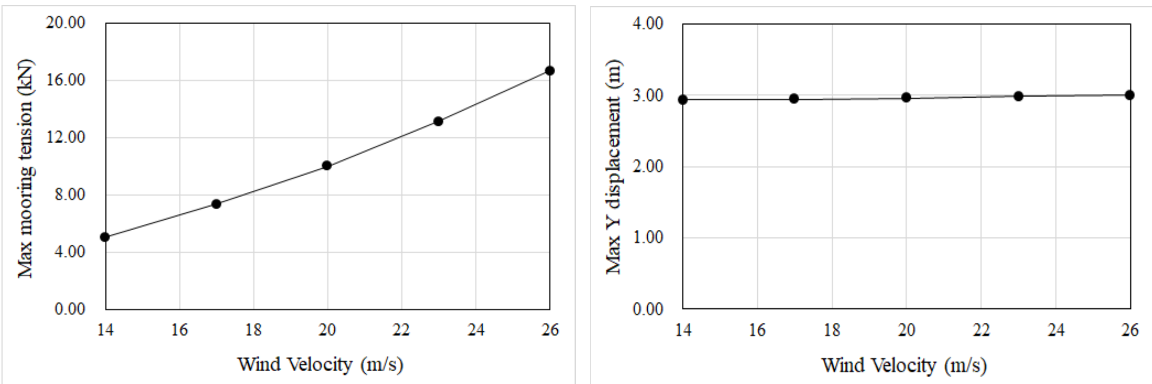
In current only conditions in Case 2, the current velocity grows from 0.4m/s to 1.5m/s as Fig.5(a). The Y displacement of the FPV array is constant 2.80m except for the case current velocity is 0.4m/s shown as Fig.5(b). Due to the shallow draft of the FPV array, the current load is small compared to the wind load. When the current velocity is 0.4m/s, the tension generated by the gravity of mooring lines counteract current load and the mooring lines are not fully tensioned. The growth of the current load leads to an augment of mooring tension while do not change displacement. Fig.5(b) also indicates that the mooring lines are slack when the motion of the FPV is less than 2.8m. It is the reason why Case 1 does not cause large mooring tension.



(a) Maximum mooring tension (b) Maximum displacement in Y direction

Fig.5 Maximum dynamic response of the FPV array in Case2

Fig.6 presents the response of the FPV in the wind-only condition (Case 3). Compared with the results in Case 1 and Case 2, it is easy to be found that mooring tension generated by wind load is much larger than that caused by the wave and current load. It means the wind is the most critical environmental parameter for the design of the mooring arrangement of the FPV array. Since the PV panel is installed obliquely, every PV panel has a projected wind area and the sum area is large. Similar to the current only case, the displacement is 2.9m and invariable.

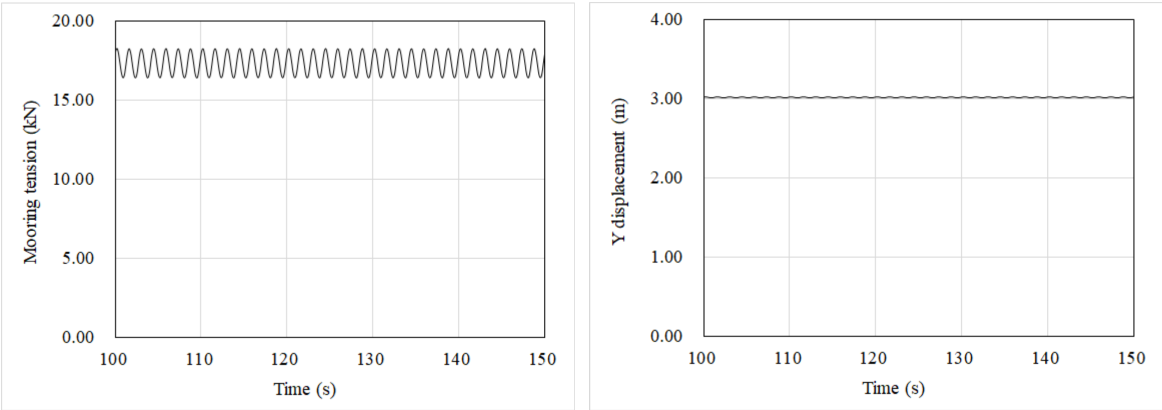


(a) Maximum mooring tension (b) Maximum displacement in Y direction

Fig.6 Maximum dynamic response of the FPV array in Case3

In Case 4 ~ Case 6, the dynamic responses of the FPV in the combined wave, wind and current condition are studied. Fig.7 provides the time history of the mooring tension and the motion of the FPV. The mooring line with the maximum tension in the FPV is selected as a typical mooring line.

The tension varies periodically since the regular wave is applied in the simulation. However, the motion of the FPV changes slightly as Fig.7(b) since the mooring lines are fully tensioned.



(a) Mooring tension (b) Displacement of the FPV

Fig.7 Time history of the mooting tension and the displacement in Case 6

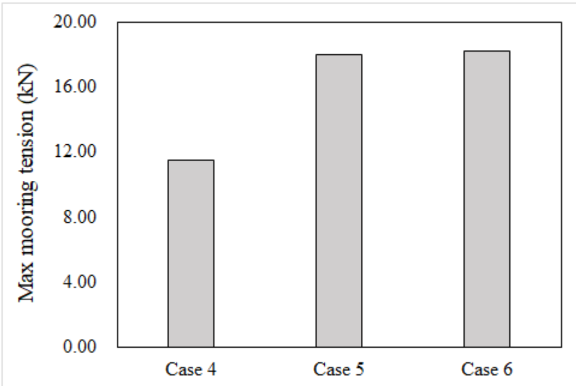


Fig.8 Maximum mooring tension in the combined load cases

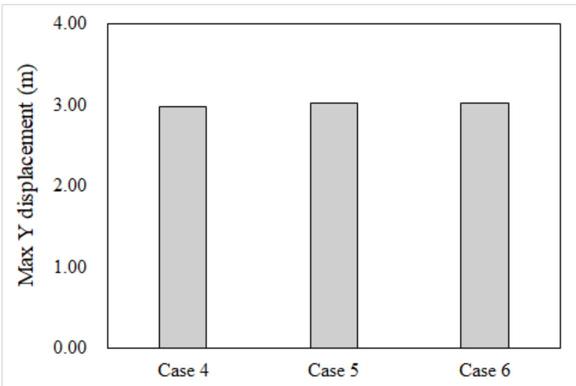


Fig.9 Maximum displacement in the combined load cases

Fig.8 and Fig.9 present the statistic tension and displacement. Fig.8 indicates that wind load is the primary load while the contribution of the wave is limited. Fig.9 shows that the changes of wind and wave have no effect on the maximum offset of the FPV.

4. Conclusion

The dynamic response of the FPV array is studied in the different environmental conditions, the conclusions are obtained as follows:

(1) The wind load is the primary load for the mooring tension and displacement of the FPV array. The mooring tension increases with the growth of wind velocity while the motion is constant.

(2) In the wave-only condition, the motion amplitude of the FPV increases when the wave heights become large, but the mooring tension is small and changes slightly since the mooring lines are not tensed.

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