

# Numerical and experimental study on hydrodynamic performance of a novel semi-submersible concept

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## Abstract

The Multiple Column Platform (MCP) semi-submersible is a newly proposed concept, which differs from the conventional semi-submersibles, featuring a centre column and middle pontoon. It is paramount to ensure its structural reliability and safe operation at sea, and a rigorous investigation is conducted to examine the hydrodynamic and structural performance for the novel structure concept. In this paper, the numerical and experimental study on the hydrodynamic performance of MCP have been performed. Numerical simulations are conducted in both frequency and time domains based on 3D potential theory. The numerical models are validated by experimental measurements obtained from extensive sets of model tests in both regular wave and irregular wave conditions. Moreover, a comparative study on MCP and two conventional semi-submersibles have been carried out using numerical simulation. Specifically, the hydrodynamic characteristics, including hydrodynamic coefficients, natural periods and motion response amplitude operators (RAOs), mooring line tension have been fully examined. The present study proves the feasibility of the novel MCP and demonstrates the potential possibility of optimization in the future study.

## Key words:

Multiple Column Platform (MCP); Semi-submersible platform; Numerical simulation; Model test; Response amplitude operators (RAOs);

## 1. Introduction

Semi-submersible has been successfully applied in offshore industry since 1960s for oil and gas resources exploitation, accommodation, power supply, because of its excellent response performance, large payload capacity and convenient relocate-ability after field abandonment (Elosta et al., 2014). Recent efforts have been made on improving the motion responses of some novel semi-submersibles. Among these designs, some focus on improving the hydrodynamic performance based on conventional semi-submersibles, while others are totally novel concept.

Of particular concern is the reduction in heave motion, which is the main purpose of improvement. One method is to increase the draft. By increasing the draft from 20~25 m to 40 m, the heave and pitch (RAO) will be reduced by approximately 50% (Bindingsbo' and Bjofset, 2002). Alternatively, the heave plates can

increase added mass and viscous damping effectively, thereby reducing heave response. This has been proved by many experiments (Tao and Dray, 2008; Thiagarajan and Troesch, 1998) and numerical studies (Molin, 2001; Tao et al., 2007). The research efforts have revealed significant insights of the fluid physics in terms of vortex shedding dynamics and associated damping mechanisms (Tao and Thiagarajan, 2003a, b). Cermelli et al. (2004) proposed a novel design, MINIFLOAT, which extended the plate area on the outside columns as heave plates to improve the motion performance in heave and pitch. Some novel semi-submersible concepts have been developed using heave plates which are supported by a structure, such as a truss, under the semi-submersible (Halkyard et al., 2002; Murray et al., 2008). Truss Pontoon Semi-submersible (TPS) is another innovative floating concept that inherits the advantages of a conventional semi-submersible and utilizes the added mass and the separated flow damping introduced by heave plates at the bottom of the truss columns, much like the Truss-Spar (Srinivasan et al., 2005). Model tests (Srinivasan et al., 2006) and numerical study (Chakrabarti et al., 2007) demonstrated the improvement in its motion characteristics. The Free-Hanging Solid Ballast Tank semi (FHS) using the free-hanging Solid Ballast Tank (SBT) significantly increases the heave natural period while controlling the heave response in the wave frequency range (Mansour, 2009); Deepwater Tumbler Platform (DTP) utilizes double tier pontoons to improve heave performance (Jiang et al., 2016).

The above studies primarily focused on the heave motion response of the existing platforms. In recent years, research efforts have also been devoted to the motion response characteristics for some novel designs. For instance, the H-pontoon semi-submersible, which consists of a pair of shorter secondary central pontoons supported by the two main pontoons, can improve the hydrodynamic performance of heave and pitch compared with conventional semi-submersibles (Mansour and Huang, 2007). A novel semi-submersible crane vessel with asymmetrical pontoons were numerically studied and significant heave-roll/heave-pitch coupling effects was found (Wang et al., 2015).

In addition, it is essential to perform the coupled analysis which focused on the global performance of semi-submersibles fitted with mooring lines and risers, since the mass and damping of them will influence the floaters' motion significantly. Qiao and Ou (2013) conducted a comparative study on the global performance of a semi-submersible. Some quantitative results were reported by the authors based on the different types of mooring systems including catenary, semi-taut and taut. Jiang et al. (2016) compared the motion and mooring loads statistics obtained from model test and coupled analysis to verify the reliability of numerical calculation and demonstrated the advantages of DTP novel semi-submersible design. Xiong et al. (2016) studied the global performance of a moored semi-submersibles based on numerical simulation and experiments, and the effect of environmental factors and mooring system on the motion responses was investigated.

Recently, the vortex-induced motion (VIM) of semi-submersibles has emerged as an important issue in offshore engineering. Since the field observations of VIM of semi-submersibles had been reported by Rijken and Leverette (2009), many studies were conducted to investigate the transverse motions (Rijken and Leverette, 2008) and yaw response (Waals et al., 2007) of semi-submersibles. Studies on how can the design of semi-submersibles influence the VIM were reported as well, e.g., mass ratio, draft (Waals et al., 2007),

hull appendages (Gonçalves et al., 2012), pontoon and column configuration (Liu et al., 2016), etc. The VIM behavior of our design will be extensively studied and presented in next paper.

In the present study, an innovative semi-submersible concept, denoted as Multiple Column Platform (MCP) semi-submersible is proposed and investigated. MCP is designed to serve as a mobile offshore power plant, which can supply energy for offshore industry, remote islands, high-power ships and seawater desalination. Due to its functional requirement, a novel design is demanded to accommodate the additional equipment, i.e., energy generate system of large size. As shown in Fig. 1, this novel design of MCP, proposed by China Ship Development and Design Center, has a unique centre column and a supporting pontoon to achieve its function. These structures can also serve as the ballast tanks provides significant displacement for the hull to reduce the heave response, increase the platform stability, topside decks capacity, and the reactor thermal efficiency due to the external cold water. The present invention provides economic, sustainability and operational advantages over the current power generator for offshore industry. Due to its unique characteristics compared to conventional semi-submersibles, essential researches are conducted to examine its hydrodynamic performance.

The hydrodynamic performance of this novel deepwater floating structures is mainly discussed and presented in this paper. In subsection 2, the description of the whole system is presented. Comprehensive numerical simulation complemented by a set of model tests are conducted to study the hydrodynamic performance of the MCP both in still water and regular/irregular wave conditions (see subsection 3, 4, 5). In subsection 6, a comparative study on the present novel design and two conventional semi-submersibles was performed in frequency domain. The hydrodynamic coefficients, RAOs, motion responses, mooring line loads are discussed in detail. Some results based on time domain analysis are also presented. The potential effects on mooring loads due to wave drift and current drag resulted from the centre column and middle pontoon are discussed.

## **2. Description of the MCP system**

### **2.1 Features of the MCP design**

In this paper, the MCP is designed to operate in the water depth of approximately 300 m in China South Sea. As shown in Fig. 1, the MCP has a principle dimension of length  $\times$  width  $\times$  depth = 100 m  $\times$  80 m  $\times$  44m, with four identical columns on the corners and a larger column in the centre. The cross-section dimensions of corner and centre column are 12 m  $\times$  12 m and 22 m  $\times$  22 m, respectively. Two parallel side pontoons both have a length of 100 m, a width of 12 m and a depth of 15 m, which are extended to support one middle pontoon perpendicular to the side pontoons. The middle pontoon is served to support the centre column. The operational draft is 25 m, the free-board is assumed to be 11 m and the total displacement of the MCP is 64418.8 MT. The metacentric height (GM) equals to 1.21 m. A scale ratio of 1:60 was selected for the model test. The main particulars of the MCP semi-submersible and model are listed in Table 1.

### **2.2 Features of mooring system**

The MCP model is positioned by a steel catenary mooring system composed of eight mooring lines, with two in each cluster. The four groups of mooring lines are laid symmetrically, and the separation angle between the mooring lines in each group is  $5^\circ$ . The mooring line is 620 m in length. Each mooring line is divided into two segments, forming a “combined-chain” structure. According to the operational requirement of the MCP and the high demand of positioning capability, the seabed chain section of each mooring line is heavier than the upper section and have an horizontal lay in the sea bottom. The main physical properties of mooring line segments are given in Table 2. To describe the layout of mooring system and the direction of the incident wave clearly, the global coordinate system (O-XYZ) is introduced (see Fig. 2).

### 2.3 Environmental conditions

Regular wave tests and white noise wave tests are carried out to obtain the motion RAOs. The white noise wave spectrum has a range from 5 to 25 s and a significant wave height of 2.5 m in full scale. Such a single white noise wave test could cover all the RAOs in regular wave tests.

The environmental conditions, listed in Table 3, are designed according to the real sea conditions in China South Sea, which include not only the operational condition but also survival conditions. The random waves are described by a three-parameter JONSWAP ( $\gamma = 3.3$ ) spectrum, and the steady wind and current are combined with irregular wave in SS.2 and SS.4. The wind, wave and current are assumed to be collinear in SS.2 and SS.4. In the model test, the four seastates were carried out at  $180^\circ$ ,  $135^\circ$  and  $90^\circ$  incident waves.

## 3. Experimental setups

The experimental program was jointly designed by Shanghai Jiao Tong University and Huazhong University of Science and Technology and the model test was carried out in the Deepwater Offshore Basin in State Key Laboratory of Ocean Engineering at Shanghai Jiao Tong University. The basin is 50 m in length, 40 m in width and the water depth can be adjusted from 0 m to 10 m with a movable bottom. Flap-hinged wave-makers are installed along two neighbouring sides of the basin and wave absorbing beaches are fixed on the opposite sides to minimize reflected wave energy from the basin boundaries. Since the operation depth of the MCP is 300 m, the water depth in the model test was set as 5 m, and the mooring system was not truncated. The moored MCP model in the basin is shown in Fig. 3.

Waves, currents and winds were calibrated prior to the model tests. The generated irregular waves spectrums are compared with target spectrums in Fig. 4. The current generator was used to simulate the design current at water surface, shown in Fig. 5. Since steady current generation in deepwater basin is still a challenge, the current velocity could not keep constant in model tests. For a 4000 seconds measurement, the current velocity was  $0.94 \pm 0.03$  m/s and  $1.93 \pm 0.08$  m/s for SS.2 and SS.4 respectively. The designed current velocity is well situated in the range of experimental measurement so that the current simulation was acceptable. This is the same method for wind simulations, i.e., the simulated wind velocity was measured over one minute for three times, until the average velocity was equal to the design wind velocity. The six DOF motions of the MCP were tracked and recorded by a non-contact optical motion capture system at the

centre of gravity. Tension transducers were utilized to measure the mooring line tensions of the semi-submersible, respectively. For each irregular wave test, the time duration is more than 23.3 min in model scale corresponding to 3 h in prototype. The sampling frequency is 25 Hz in model scale. Actually, there are three six-component force transducers located in the longitudinal mid-section of MCP model to monitor the loads on the structure. Due to the space limitation, only research on hydrodynamic issues is presented in this paper.

#### 4. Numerical model

Both frequency domain analysis and coupled analysis in time domain have been performed to examine the hydrodynamic performance of the novel MCP.

To describe the motion of the MCP system, another coordinate system is introduced: the body-fixed coordinate system (o-xyz), shown in Fig. 6. The body-fixed coordinate system is a right-handed system with the x-axis forward, the y-axis towards the port side and the z-axis upward. The origin is located at the centre of free surface for the sake of simplicity.

To obtain all the hydrodynamic coefficients of the MCP, e.g., added mass, radiation damping, first- and second-order wave-frequency and mean-drift forces, the frequency domain analysis was conducted by using SESAM HydroD, which is a program based on a diffraction/radiation panel code. Newman's approximation is used to calculate the slow-drift force (Newman, 1974), which has been proven that can obtain good results in deepwater and low frequency situation, such as surge and sway motion of floating structures (Aranha and Fernandes, 1995). The hydrodynamic damping applied in numerical simulations, including potential damping and viscous damping was obtained by the free decay tests. As for the wave drift damping of slow-drift motions, detailed calculation method is explained in DNV (2014) and will not be shown here. The underwater section of MCP is modelled with 4398 elements, as shown in Fig. 6.

The MCP/mooring coupled analysis in time domain was performed by utilizing SESAM Deep. In the coupled method mentioned here, the total loads from the slender mooring lines are modified as a force to act on the floater. The floating structure motions and the mooring dynamics are solved simultaneously at each time step. Thus, dynamic equilibrium between the forces acting on the floating body and slender mooring structure response is satisfied at every time instant. The spatially discretized system dynamic equilibrium equation is governed by (Marintek, 2014a, 2014b):

$$R^I(r, \ddot{r}, t) + R^D(r, \dot{r}, t) + R^S(r, t) = R^E(r, \dot{r}, t), \quad (1)$$

where  $R^I$ ,  $R^D$ ,  $R^S$  and  $R^E$  represent inertia force vector, the damping force vector, the internal reaction force vector and the external force vector respectively. The structural displacement, velocity and acceleration vectors are denoted by  $r$ ,  $\dot{r}$ ,  $\ddot{r}$ .

For each term in Eq. (1) specifically, the inertia force vector can be written as,

$$R^I(r, \ddot{r}, t) = M(r)\ddot{r}, \quad (2)$$

here  $M$  is the total system mass matrix which consists of structural mass and added mass. The damping force vector is expressed as,

$$R^D(r, \dot{r}, t) = C(r)\dot{r}, \quad (3)$$

where  $C$  is the system damping matrix, including both the internal structural damping as well as hydrodynamic damping. The internal reaction force vector  $R^S(r, t)$  is calculated based on the instantaneous state of stress. The last term, the external load vector  $R^E(r, \dot{r}, t)$ , accounts for the weight and buoyancy, forced displacements, environmental forces and specific forces.

In the numerical simulations, the experimental time series of the wave elevation were applied. The velocity of current and wind was set constant as designed seastates since it was hard to measure their time histories for every case. As for the current and wind force coefficients, the DNV-RP-C205 (2014) data is adopted. The finite element model of mooring lines consists of bar elements only, with mesh density of 5 m. The time step used in the computation is 0.3098s based on the convergence tests. The coupled analysis model for the MCP is demonstrated in Fig. 7. Note that these data and settings will be further verified by the experimental measurements described in the following sections.

## 5. Result and discussions

### 5.1 Free decay tests

Natural periods in six degrees of freedom can be obtained from the free decay tests. In brief, the natural period of surge, sway, heave, roll, pitch and yaw is defined as  $T_{ii}$ , where  $i=1, 2, 3, \dots, 6$ , in turn. The decay tests have been conducted in calm water with and without the mooring system respectively. For the cases without mooring system, a horizontal mooring system is provided alternatively to avoid model from drifting away. It is so soft that will not leave impact on the wave frequency motion responses. Table 4 shows the natural periods of the semi-submersible obtained both by model test and numerical simulation, and great agreement is obtained.. It is also noted that, the natural period of surge, sway, heave, pitch and yaw motion of the present MCP is close to the conventional semi-submersible. However, the nature period of roll motion is obviously longer than that of pitch motion. Generally, for the symmetrically designed semi-submersibles, the nature periods of roll and pitch will not make an apparent difference. This phenomenon can be explained by the equation of the natural period of an uncoupled and undamped floating structure (Faltinsen, 1993). To be specific, the uncoupled natural period in roll and pitch for a freely floating body can be written as,

$$T_{44} = 2\pi \sqrt{\frac{Mr_{44}^2 + A_{44}}{\rho g V \overline{GM}_T}}, \quad (4)$$

$$T_{55} = 2\pi \sqrt{\frac{Mr_{55}^2 + A_{55}}{\rho g V \overline{GM}_L}}, \quad (5)$$

where  $V$  is the displaced volume of water,  $\overline{GM}_T$  is the transverse metacentric height,  $\overline{GM}_L$  is the longitudinal metacentric height,  $r_{ii}$  is the radius of gyration and  $A_{ii}$  is the added moment coefficients.

According to the added moment coefficients by numerical simulation,  $A_{44}$ ,  $A_{55}$  is  $7.25 \times 10^{10} \text{ kg}\cdot\text{m}^2$  and  $2.59 \times 10^{10} \text{ kg}\cdot\text{m}^2$  corresponding to the roll and pitch natural period. Meanwhile, based on the MCP design,  $\overline{GM}_T$  and  $\overline{GM}_L$  are 1.21 m and 5.35 m, while  $r_{44}$  and  $r_{55}$  are 31.52 m and 32.95 m respectively. According to Eq. (5) and Eq. (6), the proportion of  $T_{44}$  to  $T_{55}$  is very close to the ratio of numerical results and model test. The difference between  $\overline{GM}_T$  and  $\overline{GM}_L$  is caused by the rectangle layout of side columns so that the transverse moment of inertia is smaller than the longitudinal moment of inertia. The significant difference

between added moments is primarily caused by the middle pontoon. Although longer nature period of roll of the MCP design appears to help avoiding wave frequency resonance, it has some drawbacks, which will be further discussed in next section.

## 5.2 RAOs

The motion characteristics for a floating structure are generally described by RAOs. The motion RAOs was derived from the measurements of model tests conducted under both the white noise and regular waves. Time series of 6 DOF motions are measured and then the spectral analyses can be conducted to acquire the power spectrum density function.

Incident wave directions and wave conditions are the same for numerical simulation. The comparison of 6 DOF motion RAOs with  $135^\circ$  incident wave angle for the MCP between the model test and the numerical simulation are illustrated in Fig. 8.

It can be seen that the motion RAOs predicted by numerical simulations show a good overall agreement with the experimental measurements. This indicates the reliability of the numerical model.

It should be noted that there is little difference for all the motions for frequency higher than approximately 0.3 rad/s (corresponding period less than 20.94 s). For low frequency ( $< 0.3$  rad/s), however, a slight difference can be observed in surge and sway motion especially due to the mooring system in the experiments. The RAOs are calculated based on the potential theory without considering any mooring system, while during the model test the semi-submersible is moored. The mooring system in the model tests has a certain influence on the low-frequency motion. The surge and sway are dominated by low-frequency motion, so that the difference is more pronounced. However, the heave motion is primarily governed by wave frequency motion. As a result, the experimental and numerical results agree well for the whole range of frequency.

## 5.3 Time domain results of motion

The model tests in irregular waves were carried out in the offshore basin with the full depth mooring system under the four seastates as shown in Table 3. Collinear environment was considered with  $90^\circ$  and  $180^\circ$  incidences respectively in this subsection, which is the same for model test and numerical simulation.

Comparisons of surge, heave and pitch motion time series at incident wave of  $180^\circ$  of SS.2 are shown in Fig. 9. The time duration (5000 s to 10000 s) is selected when the model test and numerical simulation both stabilize. In order to clearly illustrate the trend of heave and pitch motion, zoomed views are shown as well. The statistics of motions under all the four seastates at  $180^\circ$  and  $90^\circ$  incidence wavet are presented in Table 5 and Table 6 respectively. As can be seen in Fig. 9, although a slight difference between the low-frequency component of the surge motion in the full-scale numerical simulation and model test is observed, the overall comparison demonstrates a good validation of the present numerical model.

As shown in Fig. 9(a), the most pronounced discrepancy shown in surge motion due to SS.2 between the numerical simulation and experimental measurements are most likely due to the fluctuation of wind and current velocity during the model test, i.e., the difference between unsteady velocities in experiments and constant velocities in numerical simulations is the reason. As mentioned before, the current and wind are

considered to result in a drag force, which lets semi-submersible move to a mean offset in one direction, so that the horizontal motions show deviations. Furthermore, as illustrated in Table 5, the mean values and minimum values of surge motion increase markedly with the appearance of wind and current (both in SS.2 and SS.4). Similar observation has been made for sway motion, which can be seen in Table 6. It is clear that wind and current significantly influence horizontal motions, because they are dominated by low-frequency motion.

Excellent agreements are observed in Fig. 9(d), and Table 5 and Table 6 show that the maximum value and standard deviation for heave motion in both 90° and 180° remain almost unchanged due to the appearance of the severer seastates. It is a clear indication that the heave motion is governed by the wave-frequency motion. Surprisingly, the maximum heave motion become smaller due to the severer seastates. Similar phenomenon was also observed by Jiang (2016) in the model test and numerical analysis. When encountering the wind and current force in addition to random waves, the platform starts to drift away and the mooring system not only restrains the horizontal motions, but also provides additional vertical stiffness leading to decrease in heave motion.

Although the good agreement of pitch motion is obtained overall in Fig. 9(c), as shown in Table 5, the maximum value of pitch motions increases due to the wind load and current load. It further demonstrates that pitch motion, kind of motion between surge and heave, is dominated by both low-frequency and wave-frequency components. The roll motion is the same, which can be seen in Table 6

It is noted that the maximum value of roll motion is relatively high, especially for seastate SS.4, indicating that roll motion is susceptible to the wind and current influence. This disadvantage is caused by the low restoring coefficients of the MCP in roll motion. The restoring coefficients for roll and pitch can be calculated as (Lee, 1995):

$$C_{44} = \rho g \int_{S_b} y^2 n_3 dS + \rho g \nabla z_b - mgz_g \quad (8)$$

$$C_{55} = \rho g \int_{S_b} x^2 n_3 dS + \rho g \nabla z_b - mgz_g \quad (9)$$

where  $S_b$  is the mean body wetted surface,  $n_3$  is the normal vector outward water surface,  $z_b$  is the height of buoyancy centre,  $z_g$  is the height of gravity centre. For the design of the MCP, the distance between columns in longitudinal direction is longer than that in transverse direction. As a result, the first term of  $C_{44}$  ( $2.79 \times 10^8 \text{ kg}\cdot\text{m}^2/\text{s}^2$ ) is considerably smaller than that of  $C_{55}$  ( $4.80 \times 10^9 \text{ kg}\cdot\text{m}^2/\text{s}^2$ ). The low level of roll restoring coefficient results in the tough recovery of roll motion, which is the main contributor to the bad roll motion performance.

#### 5.4 Time domain results of mooring line force

The time series of the loads acting on the eight mooring lines are obtained experimentally and numerically. The results of representative mooring lines, which are subjected to the maximum loads are selected and illustrated in this subsection.

For the 180° incident wave, the comparison between the numerical results and experimental data for the mooring line #8 are given in Fig.13, showing satisfactory good agreement. It can be observed from Fig. 13

that the loads acting on the mooring lines have low frequency component which is related with surge motions. The forces also contain a certain degree of wave frequency characteristics, which are believed to be caused by the wave dynamics. The comparison of statistics of representative mooring line loads are shown in Fig. 14. It is noted that the only appearance of wind and current will influence both mean value and maximum value significantly, especially in SS. 4, in which the velocities of wind and current are much higher. Similar results can also be obtained for the 90° incident wave.

The maximum mooring line force happens in the SS.4 at the incident wave of 180°, which is 17915.12kN, equalling to 99.1% MBL. Although it does not exceed the MBL, it has already exceeded the safety criteria (66%). That is to say that further optimization should be carried out for the mooring system since the potential risk presented in the original design.

## 6 Comparative study

In order to examine whether the hydrodynamic performance of the MCP is acceptable, a comparative study is further conducted by numerical simulation in frequency domain and time domain.

### 6.1 Features of conventional semi-submersibles

To fully investigate the hydrodynamic performance of the novel MCP, two conventional semi-submersible models were analysed as benchmarks. Hull displacement and draft are vitally important for the hydrodynamic performance of a floating offshore structure (Mansour and Huang, 2007; Wang et al., 2015). Therefore, these three models have the same displacement and draft. The first conventional semi-submersible has twin identical pontoons and two columns on each pontoon, and the second one has four identical pontoons forming a ring-pontoon with four columns at each corner. For brevity and convenience, in the following sections of this paper, the novel MCP is referred to as model A. The conventional semi-submersible with two symmetrical pontoons is referred to as model B, and the conventional semi-submersible with ring-pontoons is referred to as model C. The panel models are shown in Fig. 15.

As observed in Fig. 15, the dimensions of the pontoons and the columns have to be adjusted based on their configuration to ensure the same displacement and draft as model A. For model B, the length, width and height of the pontoons are 124.62 m, 15 m and 15 m, and the section dimensions of the four columns are 15 m×15 m. The size of deck is still 100 m × 80 m. For model C, the main dimension of the pontoons is 77.31 m ×15 m ×15 m, and the section dimensions of the four columns are 15 m × 15 m. However, due to their different shapes below the water plane, the centre of buoyancy (COB) of models A, B and C are slightly different with the values 9.53 m, 9.23 m and 9.22 m, respectively. Moreover, the centre of gravity (COG) is adjusted to 19.34 m, 19.56 m and 19.23 m to ensure the similar stabilities of the models. The main parameters of model B and C are also listed in the Table 9.

### 6.2 RAOs

The comparison of motion RAOs between the three models are shown in Fig. 16. Note that the incident wave direction is not all the same for these RAOs, which is illustrated in the annotation of Fig. 16.

For surge and sway motion, as can be seen in Fig. 16(a) and Fig. 16(b), the three curves show similar trend. One can note that the surge RAO for the Model A is obviously better (with the lowest peak RAO) than the Model B and C except for the range of wave period larger than 9.2 s. It can also be seen that, for the wave period less than 10 s, the sway RAO for the novel MCP is the smallest. For wave periods larger than 10 s, these three models show little difference. Therefore, the novel MCP offers lower surge and sway RAO peak (first peak) in the fatigue range of waves especially in the South China Sea where most of the wave occurrence is with wave period less than 15 sec.

The first peak shown in surge and sway RAO is caused by the resonant water motion between the columns. For Model C, the peak in surge and sway RAO curves occur both around 7.25 s, and the half-wavelength corresponding to this wave period coincides with the distance between the columns (47.31 m). While the smaller peak sway RAO occurrence for Model B is observed, because the distance of columns in transverse direction (65 m) is smaller than that in longitudinal direction (85 m). However, the Model A does not show this characteristic. This is a clear demonstration that the unique design of centre column can prevent the violent hydrodynamic interactions which gives rise to the phenomenon. This feature also contributes to the small sway response observed for model A.

Of particular concern is the heave motion of a newly-designed semi-submersible. As observed in Fig. 16 (c) and Fig. 16 (d), the three curves show similar overall trend. All three curves exist double peaks, with the higher sharp peaks occurring at their respective resonant periods. Before the heave RAO of Model A flips at nearly 22 s, it is almost the best one. It is noted that the heave natural periods of Models A, B and C are slightly different, with values of 23.31 s, 23.85 s and 24.88 s, respectively. The deviations of the resonant periods and peak values can be explained by the equation of heave motion,

$$T_{33} = 2\pi \sqrt{\frac{M+A_{33}}{\rho g A_w}}, \quad (10)$$

where  $A_w$  is the water plane area of the floater.

For the given three models, their masses are equivalent due to the same displacement. The heave added mass  $A_{33}$  of model A, B and C at their own resonant period can be obtained by numerical calculation, are  $7.690 \times 10^7$  kg,  $6.314 \times 10^7$  kg and  $7.747 \times 10^7$  kg respectively, and the waterplane area  $A_w$  for models A, B, and C are  $1060 \text{ m}^2$ ,  $900 \text{ m}^2$  and  $900 \text{ m}^2$ , respectively. Due to the presence of middle column, the waterplane area of MCP is the largest so that its heave natural period is the smallest. However, it is still in the acceptable range for semi-submersibles and avoids most wave periods happening in the China South Sea. What's more, MCP has the smallest peak amplitude, further demonstrating that the MCP design is beneficial for the heave motion behaviour. This peak is dominated by the potential damping,  $1.840 \times 10^4$  kg/s,  $8.088 \times 10^3$  kg/s and  $3.729 \times 10^3$  kg/s, for Model A, B and C at their own resonant period, respectively. One can note that the potential damping of model A, B and C is in descending order, consistent with the increasing trend of the peak RAOs. It is the middle pontoon that produces additional damping and results in a good heave performance.

For the roll and pitch motions, which are shown in Fig. 16 (e) and Fig. 16 (f), all three curves for Model A, B and C exist two peaks, respectively. The second peak corresponds to the natural frequencies of the semi-

submersibles in roll and pitch motions respectively. To examine the second peak occurrence, the roll and pitch natural periods of three models are calculated and shown in Table 10. Excellent agreement is seen from Table 10. One should note that, even though the Model B has the same asymmetry design as Model A, its  $T_{44}$  is not larger than  $T_{55}$  so much as Model A. This is also caused by the extremely low roll restoring coefficient  $C_{44}$  of the MCP. To further demonstrate this, the roll and pitch restoring coefficients of three models are shown in Table 11. Once again, the roll motion of MCP should be improved.

### 6.3 Time domain results of motion

In fact, the motion statistics in time domain give more direct demonstration on the hydrodynamic performance in real metocean conditions. The motion statistics of three models in  $180^\circ$  incident wave and  $90^\circ$  incident wave are listed in Table 12 and Table 13, respectively. As shown in the tables, the MCP exhibits the best characteristics in the surge and sway motion in both SS.1 and SS.2 seastates. As for the heave motion, it depends on the angle of incident wave. For  $90^\circ$  incidence, heave motion of MCP is the smallest. Whereas, the heave motion of MCP is similar to Model C and slightly worse than that of Model B at incident wave of  $180^\circ$ . All of these agree with findings in 6.2. The pitch motion of MCP is slightly optimized, while the roll motion of the MCP is the worst without surprise. It can be concluded that in the designed seastates, the surge, sway motions of the MCP are obviously improved; the heave, pitch of MCP is slightly better under some circumstances; the design of the MCP should be optimized to improve its performance in roll motion.

### 6.4 Time domain results of mooring line force

Due to the larger underwater size caused by centre column and middle pontoon, it is necessary to check whether it may cause larger current drag force and wave drift force and in turn induce additional loads in the mooring system. According to the numerical simulation under the same settings, the maximum mooring line loads of three models in SS.1 and SS.2 are shown in Fig. 17. It can be seen that for both incident waves ( $180^\circ$  or  $90^\circ$ ), the maximum mooring line force for model A is the smallest, indicating that the middle column of MCP does not introduce detrimental influence on the mooring system.

To be specific, as for the current drag force which is calculated by empirical formula, the projected area of submerged section of semi-submersible is the key factor (DNV, 2014). According to the main parameters of three models, Model A has the relatively larger underwater projected area. That is to say, Model A is subject to the larger current drag force compared with the conventional models. The mean value of wave drift force of three models in SS.1 and SS.2 is shown in Fig. 18. It can be seen that for both incident waves ( $180^\circ$  or  $90^\circ$ ), the wave drift force for model A is obviously smaller than the other two models. Although the current drag of Model A is the largest under some occasions, the smallest wave drift force make Model A have better motion performance in horizontal plane and consequently less tension in the mooring system.

## 7 Conclusion

The hydrodynamic performance of a newly proposed novel semi-submersible concept, the MCP has been studied with a comprehensive numerical simulation complemented by scaled model test carried out in offshore basin. Following conclusions can be drawn from the present study.

- (1) The feasibility of the novel concept MCP is demonstrated in terms of the hydrodynamic performance based on the model test and numerical simulation. In addition to satisfying the structural and general arrangement requirements, the novel design of the centre column and pontoon brings favourable improvement in heave, surge, sway and pitch motions compared to conventional semi-submersibles.
- (2) The design of the centre column and pontoon help MCP have the smallest mooring line loads under the operation conditions compared to the conventional semi-submersibles. Although the current drag force is largest for MCP under some occasions, the smallest wave drift force of MCP gives rise to the favourable mooring system performance.
- (3) The asymmetry MCP design leads to the roll natural period almost three times as the pitch natural period. It induces relatively low roll restoring coefficients that make MCP have larger roll motion than conventional semi-submersibles under some occasions. This should be improved in the future research.
- (4) Based on the hydrodynamics analysis of the novel MCP, the low-frequency motion dominates the surge and sway motion, whereas the wave-frequency motion dominates the heave motion. Both wave-frequency and low-frequency shows significant effects on the pitch and roll motion. The wind and current influence the horizontal motions significantly.
- (5) As for the load acting on the mooring lines, it mainly presents low frequency component which is related with horizontal motions. On the other hand, it also contains a certain degree of wave frequency characteristics. The wind and current influence the statistics of mooring line loads much more obviously than wave.

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