Yu C, Hu Z, Wang S.

[Investigation of heave response of the deepwater octagonal FDP SO using various heave plate configurations.](#)

Journal of Marine Science and Application 2017, 16(4), 446-457

Copyright:

The final publication is available at Springer via <https://dx.doi.org/10.1007/s11804-017-1431-9>

DOI link to article:

<https://doi.org/10.1007/s11804-017-1431-9>

Date deposited:

21/02/2018

Embargo release date:

13 December 2018

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Investigation of heave response of the deepwater octagonal FDPSO using various heave plate configurations

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Abstract: Heave plates can be employed to control undesirable heave motion amplitudes of the deepwater octagonal floating, drilling, production, storage, and offloading (FDPSO) platform. Numerical simulations and model tests were applied to analyze and investigate the hydrodynamic response and the feasibility of the heave plate configurations. The diameter and the depth below the free surface of a single-layer heave plate, as well as the spacing of two-layer heave plates, were considered as the primary variables when studying the effect of heave plates on FDPSO hydrodynamics. The analysis results indicate that the heave plate diameter significantly affects the heave hydrodynamics, and heave performance could be improved with an increased diameter. In addition, increasing the depth below the free surface of a single-layer heave plate does not effectively suppress the heave motion within the range of draft depths tested. The target FDPSO obtained better heave characteristics with increased spacing between the two-layer heave plates. Furthermore, the global performances of the octagonal FDPSO with these typical heave plate configurations were comparatively analyzed. The results indicate that from a hydrodynamic point of view, the single-layer heave plate configuration has an advantage over the two-layer heave plate configuration.

Keywords: octagonal FDPSO; hydrodynamic; heave plate; heave motion; numerical analysis; model test

Article ID: 1671-9433(2017)04-0000-00

1 Introduction

A novel approach to oilfield development and an early production system is illustrated in the world's first floating, drilling, production, storage, and offloading (FDPSO) vessel, which was employed to develop the Azurite field in 2009(Harris *et al.*,2010). The concept of FDPSO, which combines drilling function and oil storage, improves the various shortcomings of traditional floating platforms. But the multi-functionality of FDPSO also brings more challenges and risks. Particularly, the motion response of FDPSO should

be adequately low to permit simultaneous drilling operation and positioning in sea state.

The referenced deepwater octagonal FDPSO was proposed by the China National Offshore Oil Corporation for the exploitation of oil and gas in the South China Sea. The motion response, heave in particular, must be examined to ensure safe drilling operations because of the large water plane area of the platform and the often precarious state of the South China Sea. The octagonal FDPSO without heave plates possesses low damping and a low natural period, which may lead to undesirable heave motions in serious sea states. Haslum and Faltinsen(1999) proposed three methods of reducing the wave frequency heave response: (1) increasing the damping of the system; (2) changing the natural period out of the range of the wave energy; and 3) reducing the linear heave excitation force. Li *et al.*(1999) revealed that appendages, such as a disk, could be added to the keel of a vertical cylinder to effectively increase the damping. Tao *et al.*(2004) also indicated that the natural heave period of a spar platform could be effectively increased by increasing the draft, mass, and the added mass of the structure, or by decreasing the water plane area. Nevertheless, increasing the draft and subsequently increasing the system mass typically requires several additional design considerations. Hence, an optimal solution is to increase the damping of the system and natural period by applying heave plates to the octagonal FDPSO.

Heave plates have been widely applied to control the amplitude of the heave motion of a floating unit. Many studies have been conducted on heave plates because of their extensive application. Most of the relevant studies have focused on the influence of various heave plate geometrical parameters, including the number, the spacing and the thickness of the heave plating, and the shape and the size of the openings on the heave plating. Prislin *et al.*(1998) conducted a study on the damping effects of a single plate and of two-plates and concluded that the interference phenomenon of two-plates could be ignored with increased spacing. Tao *et al.*(2007) studied the influence of spacing effects of heave plate damping on offshore structures and revealed that the configuration of a cylinder with two disks may produce lower damping and additional mass relative to a cylindrical disk due

Received date:

Accepted date:

Foundation item: China National Scientific and Technology Major

Project (Grant No. 2016ZX05028)

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to suppressed vortex shedding between the two disks with a small relative spacing. Dowine *et al.*(2000) performed an experiment with small and large plates, and the results indicated that plates extending beyond the platform significantly improved the behavior of the platform. Shen *et al.*(2002) investigated the hydrodynamic characteristics of heave plates with different form edges within a Truss Spar Platform and revealed that the hydrodynamic performance of tapered heave plates exceeds that of the original design within a certain range. Both Zhang *et al.*(2006) and Tao *et al.*(2008) compared the performance of perforated plates with that of solid plates and concluded that satisfactory heave motion characteristics could be obtained by using heave plates with a proper hole-to-area ratio. Li *et al.*(2013) investigated the hydrodynamic coefficient of heave plates by using forced oscillation model tests. He analyzed the effect of the shape of the edge, perforation ration, and other geometrical variables on the hydrodynamic coefficients. Thus, the conclusions were consistent with previous investigations. Lavrov and Soares(2016) investigated the laminar flow around heaving axisymmetric and three-dimensional cylinders with damping plates for various Keulegan-Carpenter numbers through a numerical method. Lopez-Pavon and Souto-Iglesias (2015) investigated the hydrodynamic coefficients of heave plates by a comparative model test. With the numerical simulation results and the model testing results, they compared the hydrodynamic coefficients of heave plates equipped with a vertical flap at its edge with that of plain heave plates, and revealed that the damping and added mass shows little dependence on the frequency but a large dependence on the motion amplitudes. Philip *et al.*(2013) compared the hydrodynamic performance of a spar hull by using model test methods and CFD simulations, and it was revealed that a reduced heave response could be achieved when a suitable spacing between the heave plates could be adopted. Garrido-Mendoza et al.(2015) conducted analysis on flow features and hydrodynamic coefficients around heave plates oscillating near a seabed.

Challenges introduced by the application of heave plates to the octagonal FDPSO, which differs from other offshore floating structures, due to the octagonal FDPSO having a larger water plane area, ring-form arrangement of heave plates and the range limitation of the heave plate location. These challenges may bring different heave motion responses.

This paper presents an investigation of the influence of heave plates on the heave motion response of the octagonal FDPSO. Heave response for various configurations were investigated using numerical analyses and model tests, and the following three key factors influencing the heave response of FDPSO were investigated:

- (1) The diameter of the heave plates;
- (2) The installation depth of a single-layer heave plate;
- (3) Spacing between the two-layer heave plates.

The reference octagonal FDPSO has a maximum of two

layers of heave plates. A discussion and comparison of the results are presented, and recommendations are presented for applicable heave plate design. Moreover, the global performance of the octagonal FDPSO with applicable heave plates design could be obtained; thus, this study presents an improved design and operation plan for the octagonal FDPSO.

The text should contain an Introduction that puts the paper into proper perspective for the reader, and should also contain Methods, Results, Discussion, and Conclusion sections.

2 Theory background of hydrodynamic calculation

According to Prislin *et al.*(1998), the hydrodynamic forces on a heave plate can be calculated using the Morison formulation:

$$F = F_d + F_i = \frac{1}{2} \rho U |U| L^2 C_d + \rho \frac{\partial U}{\partial t} L^3 C_a \quad (1)$$

where F_d and F_i are the drag and inertial forces, ρ is the fluid density, U is the relative velocity, L is the plate width, C_a is the added mass coefficient, $\frac{\partial U}{\partial t}$ is the acceleration perpendicular to the plate, and C_d is the drag coefficient.

Then,

$$C_a = \frac{F_i / \frac{\partial U}{\partial t}}{\rho L^3} = \frac{m_a}{\rho L^3} \quad (2)$$

$$C_d = \frac{F_d / U^2}{\frac{1}{2} \rho L^2} = \frac{f_d}{\rho L^2} \quad (3)$$

where m_a is the added mass and f_d is the drag force under unit acceleration and unit velocity.

The principle of linear-induced motions and loads on large floating structures is adopted in this paper to obtain the hydrodynamics of FDPSO. Additionally, both frequency-domain and time-domain analyses are performed.

2.1 Frequency-domain analysis

The potential theory is adopted to calculate the first-order radiation and diffraction effects on large volume structures. The potential flow assumption allows the velocity flow to be defined as the gradient of the velocity potential Φ that satisfies the Laplace equation:

$$\nabla^2 \Phi = 0 \quad (4)$$

in a fluid domain(Lee and Newman, 2005) A consequence of the harmonic time dependence incident wave, a complex velocity potential ϕ related to Φ could be defined as:

$$\Phi = \text{Re}(\phi e^{i\omega t}) \quad (5)$$

where Re is the real part, ω is the frequency of the incident wave, and t is time. The linearized free-surface boundary

theory is introduced to solve the boundary-value problem. Linearization permits decomposition of the velocity potential ϕ into radiation and diffraction components:

$$\phi = \phi_R + \phi_D, \quad (6)$$

$$\phi = i\omega \sum_{j=1,6} \xi_j \phi_j, \quad (7)$$

$$\phi_D = \phi_0 + \phi_i, \quad (8)$$

where ϕ , ϕ_R , and ϕ_D are the total, radiation, and diffraction velocity potentials, respectively. The constant ξ_j denotes the complex amplitude of the body oscillatory motion in six rigid-body degrees of freedom (DOF), and ϕ_j is the corresponding unit-amplitude radiation potential. The velocity potential ϕ_i represents the scattered disturbance of the incident wave by the body fixed at an undisturbed position. The total diffraction potential ϕ_D denotes the sum of ϕ_i and the incident wave potential ϕ_0 .

The boundary-value problems can be solved using Green's theorem according to the boundary conditions.

The equation of the rigid-body motion in 6-DOF in the frequency domain is as follows (DNV, 1993):

$$[M + a(\omega)]\ddot{\xi} + (C(\omega) + C_{plate})\dot{\xi} + K\xi = F(\omega) \quad (9)$$

where M is the generalized mass matrix for the ship hull, $a(\omega)$ is the added mass matrix, $C(\omega)$ is the wave damping matrix, C_{plate} is the damping due to the heave plate, ξ is the displacement of the ship hull, K is the hydrostatic restoration stiffness matrix, and $F(\omega)$ is the external force vector caused by wave motion, mooring, and other forces. Eq. (9) suggests that the body motions corresponding to the first-order wave excitation forces can be written as follows:

$$\xi^{(1)}(\omega) = RAO(\omega) \cdot F^{(1)}(\omega), \quad (10)$$

where the superscript (1) represents the first-order variables, and $RAO(\omega)$ is the response amplitude operator, which can be expressed as follows:

$$RAO(\omega) = \{-\omega^2 [M + a(\omega)] - i\omega C(\omega) + K\}^{-1}. \quad (11)$$

2.2 Time-domain analysis

The coupling effects between the hull and the mooring lines cannot be ignored because of FDP SO's large displacement and the length of the mooring lines; hence, the frequency-domain analysis is not sufficient, and a coupled analysis in a time domain must be performed. The motion equations of time-domain coupling analysis for FDP SO are described as follows (DNV, 2005, Rho, 2007):

$$[M + a(\infty)]\ddot{\xi} + \int_{-\infty}^t [h(t-\tau)]\dot{\xi} d\tau + K\xi = F^{wave} + F^{current} + F^{wind} + F^{ext} \quad (12)$$

where F^{wave} , $F^{current}$, and F^{wind} denote the wave, wind, and current drag forces, respectively. The last item F^{ext} represents all other external forces (specified forces, forces from

station-keeping, and coupling elements, etc.), and $h(t)$ refers to the retardation function matrix, or the influence of the memory effect on the free surface, and it can be obtained using the following equation:

$$h_{ij}(t) = \frac{2}{\pi} \int_0^\infty C_{ij}(\omega) \cos(\omega t) d\omega \quad (13)$$

It should be noted that damping on the vessel from viscous skin drag, wave drift damping, and radiation damping should also be included in $\frac{2}{\pi} \int_{-\infty}^t [h(t-\tau)]\dot{\xi} d\tau$ in the form of critical damping, because these variants are related to the motion velocity of the vessel.

3 Description of the deepwater octagonal FDP SO system

3.1 Features of the octagonal FDP SO

The reference FDP SO is octagonal in shape and includes a rectangular moon pool in the center of the hull. The moon pool contains a variable cross-section at half height. The octagonal FDP SO system is expected to be located at a water depth of 2000 m. The primary parameters of the reference FDP SO are presented in Table 1. The octagonal FDP SO is moored by 16 mooring lines separated into four bundles. The angle gap between the two adjacent bundles is 75°, as shown in Fig. 1. Each line has three chain-wire-chain segments with a horizontal span of 3750 m. The pretension force acting on the top of each mooring line is 2,900 kN. The primary parameters of the mooring system are presented in Table 2.

Table 1 Primary parameters of the reference FDP SO

Designation	Unit	Fully loaded
Length over all	m	80
Breadth	m	80
Depth	m	40
Draft (-h)	m	13.9
Displacement	ton	80811
Center of gravity above keel	m	24.15
Radius of roll gyration	m	31.13
Radius of pitch gyration	m	31.17
Radius of yaw gyration	m	35.05

Fig. 1 Mooring system of FDPSO.**Table 2 Main properties of the mooring system**

Designation	Length	Diameter	Weight in air	Weight in water	Axial stiffness
Unit	m	mm	N/m	N/m	N
Chain	125	152	4493.4	4311.1	1.74E+09
Polyester	2800	274	710.95	118.6	2.68E+08
Chain	150	152	4493.4	4311.1	1.74E+09

3.2 Heave plate features

The diameter, draft depth, and spacing of the heave plates were considered in this research. Because the heave plate is a regular octagon, then the diameter of its circumscribed circle is defined as the diameter of the heave plate. A series of diameters referred to as “D” in Fig. 2(a) were studied: 95.25 m, 99.58 m, 103.91 m and 108.24 m. In addition, the distance from the free-surface waterline to the midline of the heave plate is defined as the draft depth of the heave plate. A series of draft depths referred to as “H” in Fig. 2(b) were studied: 6.9 m, 8.9 m, 10.9 m and 12.9 m. Similarly, the distance between the midlines of the two-layer heave plates is defined as the spacing of the heave plates. It is noteworthy that the lower heave plates were fixed, and the spacing was changed by adjusting the upper heave plates when investigating the spacing effects. A series of spacings referred to as “S” in Fig. 2(c) was studied: 4m, 5m, and 8 m. Details of the heave plates are listed in Table 3.

(a).Diameter of the heave plate (Top view) (b) Draft depth of the heave plate (Front view) (c) Spacing between the two-layer heave plates (Front view)

Fig. 2 Various heave plate configurations and non-dimensional parameters.**Table 3-1 Primary properties of the heave plates with various diameters**

Configuration	1	2	3	4
Diameter of heave plates/m	95.25	99.58	103.91	108.24
Heave plates quantities	1	1	1	1
Draft depth of heave plates/m	12.9	12.9	12.9	12.9
Non-dimensional value of draft depth to diameter	0.135	0.130	0.124	0.119

Table 3-2 Primary properties of the heave plates with various draft depths

Configuration	1	2	3	4
Draft depth of heave plates/m	6.9	8.9	10.9	12.9
Heave plates quantities	1	1	1	1
Diameter of heave plates/m	108.24	108.24	108.24	108.24
Non-dimensional value of draft depth to diameter	0.064	0.082	0.101	0.119

Table 3-3 Primary properties of the heave plates with various spacings

Configuration	1	2	3
Spacing of heave plates/m	4	5	8
Heave plates quantities	2	2	2
Diameter of heave plates/m	108.24	108.24	108.24

3.3 Environmental conditions

Irregular sea environment, including wave, wind, and current forces, were applied in this study to the octagonal FDPSO system. The random wave component is described using a three-parameter Jonswap spectrum with a significant wave height (H_s), spectrum peak period (T_p), and peak enhancement factor (γ). Steady flow is assumed for both the wind and the current. The irregular wave, wind and current approach for the FDPSO system with a heading of 150° used within the numerical simulations and the model tests is shown in Fig. 1. Details of the environmental conditions are listed in Table 4.

Table 4 Sea environment conditions

Designation	Random wave				Random wind		Random current		
	H_s (m)	T_p /s	γ	Heading	V_w / m/s	Heading	V_c / m/s	Heading	
One-year return sea state	6.2	11.1	2.0	150°	19.3	150°	1.05	150°	
One-hundred-year return sea state	15	18	2.4	150°	49.5	150°	1.95	150°	

4 Numerical modeling

The frequency-domain and time-domain analyses were performed by the well-known hydrodynamic software SESAM to calculate the hydrodynamic characteristics of the octagonal FDPSO with various heave plate configurations. The RAOs were obtained using the hydrodynamics analysis module HydroD, which is contained within SESAM. Hydrodynamic models of the referenced FDPSO with various heave plate configurations are shown in Fig. 3. From Fig. 3, each of the heave plates are modeled by two layers of panel elements that are placed very close. The upper layer of panel elements bears a hydrodynamic load from above, and the lower layer of panel elements bear hydrodynamic load from below, which guarantees that both sides of the heave plate possess a hydrodynamic property. The distance between the two layers is the thickness of the heave plate, and since the thickness property of the panel model is not included in the modeling, such a close distance between the two layers is practicable. In addition, there are no panel elements built on the brims between the two layers, and the hydrodynamic load applied on the brims are neglected.

(a) Single-layer heave plate at bottom of hull (b) Single-layer heave plate at a certain draft depth (c) Two-layer heave plates with a certain spacing
Fig. 3 Various hydrodynamic models of the octagonal FDPSO
Coupled time-domain analyses were performed using the module DeepC.

The coupled model for FDPSO is shown in Fig. 4. The mooring lines model is simulated by a truss member in DeepC. Data from the wind and current tests were adopted for the wind and current load coefficients on the body.

Fig. 4 The global coupled analysis model of the octagonal FDPSO system

5 Model tests

A series of model tests were conducted in the Deepwater Offshore Basin at Shanghai Jiao Tong University. The basin has scantling dimensions of 50 m in length, 40 m in breadth and 10m in depth(Lu et al., 2006, Stansberg,2002). The scaling factor at 1:60 was selected.

The octagonal FDPSO model consists of glass fiber-reinforced plastic and wood. Dismountable heave plates were adopted to achieve different heave plate spacing. The mass characteristics were confirmed by distributing the weights in various positions of the model. The model is shown in Fig. 5.

Fig. 5 Deep water octagonal FDPSO model

The mooring system of the ultra-deep floating system cannot be accommodated in both horizontal and vertical planes because of limitations in the available water basins. Thus, the mooring system requires truncation to a water depth of 350 m in the prototype(Ward et al.,2004, Su et al.,2009, Fan et al.,2014). Details of the truncated mooring system in the prototype are listed in Table 5. Comparison results of the horizontal stiffness characteristics of mooring systems are shown in Fig. 6.

Table 5 Primary properties of the truncated mooring system

Designation	Length	Weight in water	Axial stiffness
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Fig. 6 Comparison of horizontal force excursion plots of mooring systems

Decay tests were initially conducted to obtain the natural period and non-dimensional damping coefficients in a still water condition. White noise sea tests were conducted to obtain the RAO of the platform. During the white noise sea tests, the platform was moored by four soft lines, which were evenly distributed around the basin. The soft line consists of springs and chains, restricting slowly varying horizontal motions but not significantly affecting any motions induced at wave frequency.

Only bodies with a single-layer heave plate at a draft depth of 12.9 m and two-layer heave plates with a spacing of 5 m were tested in irregular sea states. One-year return and 100-year return sea states were selected, and it combines irregular waves, steady winds, and currents. The objective was to test the motion response and mooring force of the octagonal FDPSO system in specific sea states in the South China Sea. The bodies with various heave plates were tested at the quartering (150°) sea states. A photo of the FDPSO system in irregular wave sea state is shown in Fig. 7.

Fig. 7 Snapshot from the irregular wave tests

6 Results and discussions

Frequency-domain and time-domain analyses were performed to investigate the applicable heave plate configurations, and the numerical model was calibrated according to the model tests calibration results.

The influence of diameter and draft depth of the single-layer heave plate, as well as the spacing of two-layer heave plates, is presented in this section. Numerical simulations were conducted for each heave plate configuration. A single-layer heave plate at a draft depth of 12.9 m and two-layer heave plates with a spacing of 5 m were tested in irregular waves. The numerical analysis models illustrated in this section were calibrated according to experimental data. In the last part of this section, the heave response and the mooring line tension force were analyzed to draw an applicable heave plate configuration.

6.1 Influence of the heave plate diameter

Four different heave plate diameters (95.25, 99.58, 103.91, and 108.24 m) were adopted to investigate the influence of heave plate diameter on the heave motion response of the octagonal FDPSO. The natural periods and non-dimensional damping coefficients are listed in Table 6, which includes numerical results and experimental data. The non-dimensional damping coefficient was derived from the decay tests in still water.

Table 6 Natural period T(s) and non-dimensional damping coefficient μ of the octagonal FDPSO with various heave plate diameters

Diameter of the heave plate (m)	Natural heave motion period(s)		Non-dimensional damping coefficient μ	
	Calculation	Model test	Model test	
No heave plates	12.928	/	/	
95.25	12.955	/	/	
99.58	13.368	/	/	
103.91	14.120	/	/	
108.24	14.784	14.64	0.045	

Form Table 6, the application of heave plates significantly increases the natural heave motion period. Furthermore, the natural heave motion period increases with the increase of the heave plate diameter. Thus, it can be pointed out that the variation in the diameters can significantly influence the natural heave motion period. This correlation can be explained by the investigation results of Tao and Thiagarajan(2003), who revealed that the diameter ratio of the cylinder and the heave plates could have a significant impact on the added mass. Additionally, Thiagarajan et al.(2002)revealed that the added mass coefficient was linear with the third power of the diameter ratio for a certain range of Keulegan-Carpenter (KC)number, indicating a weak influence of KC.

A heave decay test was conducted to obtain the natural period and non-dimensional coefficient of the octagonal FDPSO when the diameter of heave plate is 108.24 m. The experimental results are listed in Table 6, and the heave decay curve of the model testing is shown in Fig. 8.

Fig. 8 Heave decay test curve of the FDPSO (D means diameter of heave plate)

Fig. 9 Comparisons of RAO curves with different heave plate diameters

The amplitude of the heave motion response of the FDPSO can be reduced by increasing the diameter of the

heave plates. Fig. 9 shows the RAO curves for the heave motion according to different heave plate diameter configurations. Numerical simulations and experiment data match well. It is indicated from Fig. 9 that the heave response of the FDPSO becomes smaller when the diameter of the heave plate increases under the condition when the wave period is less than 14.5 s. This proves an expected effect on reducing heave response through increasing the diameter of the heave plate. Nevertheless, the RAO curve of heave motion for the FDPSO without the heave plate is intentionally not included in Fig. 9, to exclude the influence of a viscous effect coefficient that may lead to different peak value with different viscous effect coefficient definition.

Furthermore, it is also indicated from Fig. 9 that the peak value of heave RAO becomes larger as the diameter of the heave plates increases, which may be due to the reason that longer waves can induce larger heave motion amplitude on the floater with larger scantling, because the heave plate influences the scantling diameter of the FDPSO to some extent. More importantly, this tendency may also be due to the neglect of the viscous damping effect of the FDPSO hull in the numerical calculation. Simulations were performed without considering the difference of viscous damping of various heave plate diameters in Fig. 9. It is pointed out that the vortices within higher heave plate diameters are rounder and appear to move without hull hindrance, which may lead to large viscous damping (Tao and Cai, 2005). Hence, considering the difference in viscous damping of various heave plate diameters may deduce different results. In addition, besides the amplitude of the heave RAOs, it is also shown in Fig. 9 that the resonant peak period of heave motion increases when the diameter of the heave plate increases. This change again proves that the variance of the diameter of the heave plate is one of the major factors dominating the heave motion response.

Table 7 Summary of the heave motion statistics of the octagonal FDPSO with a single-layer heave plate at different diameters. (The irregular wave, wind, and current approaches of the octagonal FDPSO system with a heading of 150°)

Designation	Diameter	One-year return sea state				One hundred-year return sea state			
		Max	Min	Mean	STD.	Max	Min	Mean	STD.
Heave (m)	D=95.25 m	1.92	-1.98	0.01	0.57	12.53	-12.03	-0.002	3.09
	D=99.58 m	1.80	-1.81	0.01	0.50	12.40	-11.94	0.004	3.08
	D=103.91 m	1.56	-1.52	-0.05	0.39	12.04	-11.94	-0.06	3.05
	D=108.24 m	1.19	-1.14	0.001	0.28	11.60	-11.53	-0.003	2.98
	D=108.24m (Experimental data)	1.12	-1.14	0.00	0.35	11.74	-10.54	0.01	3.07

Fig. 10 Partially enlarged drawing of the time series of the heave motion response for various heave plate diameters in the one-hundred-year return sea state.

Under severe sea states, the damping effect of heave plates with large diameter may be lessened by the wave-induced load applied on the heave plates. Table 7 shows the heave motion statistics of the octagonal FDPSO with a single-layer heave plate at different diameters. Fig. 10 shows a time series of heave motion responses for various heave plate diameters in the one-hundred-year return sea state. From Table 7, the maximum value of the heave response is reduced with increasing diameters and Fig. 10 further substantiates this tendency. But it can also be pointed out from Table 7 and Fig. 10 that the differences between the heave responses become minimal at the one-hundred-year return sea state, because the wave-induced load plays a dominant role for large diameter heave plates, and the wave-induced load lowers the damping effect of the heave plates. This phenomenon also proves that the heave plates should be installed at a deep position on the hull.

In conclusion, fundamentally, the heave motion response of the FDPSO can be reduced by increasing the diameter of the heave plates for most of the sea states. Nevertheless, under severe sea states, the large diameter may also bring some disadvantageous effect due to the wave-induced load on the heave plates.

6.2 Influence of draft depth on the single-layer heave plate

Four draft depth values (6.9 m, 8.9 m, 10.9 m, and 12.9 m) were employed in the numerical simulations to investigate the influence of heave plate draft depth on the heave motion response of the octagonal FDPSO; though for saving testing cost, only the 12.9 m draft depth was employed in the model test. Both the decay test and white noise tests were performed for this depth condition. The natural periods and

non-dimensional damping coefficients are presented in Table 8. The non-dimensional damping coefficient of 12.9 m draft depth is presented and used as a calibration basis for numerical simulation calibration. Fig. 11 compares the RAO curves at different heave plate draft depths for heave motion responses. It observed that numerical simulations and experiment data match well.

Table 8 Natural period T(s) and non-dimensional damping coefficient μ of octagonal FDPSO with various heave plate draft depths

Draft depth of heave plates (m)	Natural heave motion period(s)		Non-dimensional damping coefficient μ
	Calculation	Model test	Model test
6.9	14.568	/	/
8.9	14.592	/	/
10.9	14.682	/	/
12.9	14.784	14.64	0.045

Fig. 11 Comparisons of RAO curves with different heave plate draft depths

From Fig.11 the natural period of heave motion is insensitive to the changing of the draft depth of the heave plate, and only a slight increase is expected near the resonant period for the FDPSO with a heave plate draft depth of 12.9 m. The difference in the RAO amplitude is too small to be considered. Thus, the applicable draft depth of heave plates could be 12.9 m if a single heave plate is required. This result is also verified by the calculation in the time-domain analysis. In Table 9, the summary of the heave responses for FDPSO with different heave plates draft depths are presented and the heave responses of FDPSO in time series under the one-hundred-year sea state are presented in Fig. 12.

Table 9 Summary of the heave motion statistics of the octagonal FDPSO with a single-layer heave plate at different draft depths. (The irregular wave, wind, and current approaches for the octagonal FDPSO system with a heading of 150°)

Designation	Draft depth	One-year return sea state				One hundred-year return sea state			
		Max	Min	Mean	STD.	Max	Min	Mean	STD.
Heave	H=6.9m	1.12	-1.16	0.01	0.26	11.32	-11.10	0.001	2.86

Fig. 12 Partially enlarged time series of the heave motion responses for various draft depths of heave plates in the one-hundred-year sea state

The difference due to the variance of draft depths of the heave plates can be neglected. Table 9 shows that the response amplitude of heave motion changes minimally with the increase of heave plate draft depth, and it is confirmed by the time-series curves in Fig. 12. Hence, it is indicated that the draft depth of the heave plates contributes little to the improvement of heave motion performance under this condition because of the limited draft of FDPSO compared to that of the prevailing Spar platform. Further studies may include heave plates placed under the floating body at a certain draft depth rather than placing the heave plates at the bottom of the hull. Nevertheless, to install the heave plates at a deeper position may be related to some other factors, such as additional structural components, fatigue problems, and the installation operation concerns. Consequently, the present applicable location of the heave plates should be 12.9 m at the bottom of the hull, provided a single-layer heave plate is required.

6.3 Influence of two-layer heave plates spacing

When the two-layer heave plates design is adopted, the spacing between the two heave plates is one of the key factors that should be considered. In this study, three spacing values (4 m, 5 m, and 8 m) were adopted in the numerical simulations to investigate the influence of the spacing between two heave plates on motion response, and the three spacing cases were all employed in the decay model testing. The flow field of the two heave plates is more complex than that of a single-layer heave plate. Moreover, viscous damping is difficult to estimate because the vortex shedding between the two disks may be suppressed in a smaller spacing. Hence, decay tests for the FDPSO with heave plates spacing of 4 m, 5 m, and 8 m were conducted respectively, and the corresponding values of natural period and non-dimension damping coefficient μ were all obtained. The numerical simulations were calibrated to ensure

adequate comparisons with the test model.

The natural period and non-dimensional damping coefficient results with various spacing values are listed in Table 10. The time series of the curves of heave decay motions of the FDPSO with various spacing are shown in Fig. 13. Fig. 14 presents the RAO curves of heave motion for different heave plate spacing. The numerical simulations and experimental data show good comparison matching.

Table 10 Natural period $T(s)$ and non-dimensional damping coefficient μ of the octagonal FDPSO with various spacing

Spacing between two-layer heave plates (m)	Natural motion period(s) Calculation	heave motion period(s) Model test	Non-dimensional damping coefficient μ Model test
4	15.63	15.51	0.042
5	15.79	15.73	0.044
8	16.54	16.27	0.049

From Table 10, the octagonal FDPSO achieves large natural heave periods when the spacing between the two-layer heave plates increases. Thus, increasing the spacing of the heave plates is effective in expanding the natural heave motion period. In addition, the natural heave motion period increases quite significantly when the spacing is 8 m because the added mass and damping of the system increase as the spacing of the heave plates increases. In addition, a positive correlation was also observed between the spacing and non-dimension damping coefficient, as illustrated in Table 10. It means that when the spacing value increases, the non-dimensional damping coefficient also increases, which is due to the reason that large spacing benefits the flow separation and vortex shedding, though this increase is not large.

Fig. 13 Heave decay test curves of the FDPSO with various spacings

Table 11 Summary of the heave motion statistics of the octagonal FDPSO with two-layer heave plates under different spacing. (The irregular wave, wind, and current approaches for the octagonal FDPSO system with the heading of 150°)

Designation	Spacing	One-year return sea state				One hundred-year return sea state			
		Max	Min	Mean	STD.	Max	Min	Mean	STD.
Heave (m)	S=4m	1.29	-1.19	0.01	0.31	12.60	-12.89	-0.01	3.40
	S=5m	1.25	-1.12	0.01	0.29	12.48	-12.54	-0.01	3.36
	S=5m(Experimental data)	1.08	-1.15	-0.05	0.29	12.44	-11.52	-0.06	3.25
	S=8m	1.07	-1.01	0.01	0.30	11.71	-11.92	-0.01	3.18

Fig. 14 Comparisons of RAO curves with different heave plate spacings

The RAO curves of heave motion obtained from the model tests and numerical simulations are compared and shown in Fig. 14. The results of the model tests and those of the numerical calculations match well. The maximal value for the heave motion response amplitude of the FDPSO system and variation in the natural period are noteworthy. The RAO heave motion curves in Fig. 14 indicate that spacing between two layers of heave plates has a slightly positive effect on the amplitude of the RAO.

In addition, it can also be pointed out that there is peak period shift when the distance between two heave plates becomes 8 m. This shift is due to the distance between two heave plates are quite large for the 8-m case, and the upper heave plate is close to the free surface, which makes the heave response more sensitive to long wave lengths. A similar peak period shift can also be observed in Fig. 9 when comparing the RAOs for heave plates with different diameters. When the diameter of the heave plate increases, the natural period of heave peak also shows a tendency to shift to larger wave periods. Consequently, it can be summarized that both increasing heave plate diameter and increasing heave plates spacing can induce more response to large wave periods.

Fig. 15 Partially enlarged time series of heave motion response for various heave plate spacing in the one-hundred-year return sea

A large spacing value between two layers of the heave plates benefits the heave response of the FDPSO to some extent. Heave motion statistics of the reference FDPSO for various heave plate spacing in the time-domain coupled analysis are given in Table 11. Fig. 15 shows the time series of heave motions with various spacing in the one-hundred-year return sea state. Table 11 shows that the heave motion response decreases when the spacing between heave plates increases, indicating that the spacing of the two-layer heave plates improves the hydrodynamic performance of FDPSO because fluid flows around the heave plates more adequately and the interference between the two heave plates is weak when the spacing is large. This

phenomenon also can be proved in the time series of heave motion, as shown in Fig. 15. From this point of view, the applicable theoretical spacing should be 8 m, which is the largest design value. However, it must be noted that heave plates can also be exposed to wave-induced load in severe sea conditions, thus causing direct wave load on the heave plates and increasing the heave motion response. Thus, the upper layer heave plates should not be placed too close to the water surface, and the best choice is 5 m for the referenced FDPSO in real engineering practice.

6.4 Comparison of hydrodynamic performance of the octagonal FDPSO with two typical heave plate configurations

Considering the coupling effects between the mooring system and the vessel, which refer to viscous damping, inertial load, and current force, a global performance investigation on the octagonal FDPSO in the time domain is necessary for reliable forecasting. According to sections 6.2 and 6.3, two typical heave plate configurations are chosen to complete the analysis, one configuration is the single-layer heave plate at a draft depth of 12.9 m and the other configuration is the two-layer heave plates with a spacing of 5 m. Thus, a comparison was performed in this section to assess the useful heave plate configurations. Table 12 shows the comparison of the statistical results of the 6-DOF motions of the octagonal FDPSO. Additionally, the comparison of heave RAOs is shown in Fig. 16, and the time series of the heave motion responses is presented in Fig. 17.

Table 12 Comparison of the motion statistics of the FDPSO with a single-layer heave plate and two-layer heave plate configurations

Motion	Unit	Heave plates configuration	One-year return sea state				One-hundred-year return sea state			
			Max	Min	Mean	STD.	Max	Min	Mean	STD.
Surge	m	Single-layer heave plate configuration	0.61	-36.03	-16.51	4.69	-36.40	-99.06	-57.46	7.88
		Two-layer heave plates configuration	-4.30	-35.37	-17.50	4.75	-40.17	-103.35	-61.75	8.85
Sway	m	Single-layer heave plate configuration	2.81	-2.43	0.24	0.92	54.99	25.79	39.46	4.17
		Two-layer heave plates configuration	3.36	-2.02	0.40	0.88	59.52	30.29	42.86	4.04
Heave	m	Single-layer heave plate configuration	1.12	-1.14	0.00	0.35	11.74	-10.55	0.01	3.07
		Two-layer heave plates configuration	1.08	-1.15	-0.05	0.29	12.84	-11.12	0.34	3.25
Roll	deg	Single-layer heave plate configuration	0.58	-0.60	0.08	0.15	4.05	-5.18	-0.52	1.06
		Two-layer heave plates configuration	0.84	-1.34	0.00	0.26	4.50	-4.89	-0.52	1.21
Pitch	deg	Single-layer heave plate configuration	2.39	-3.01	0.00	0.60	5.87	-8.14	-0.89	1.69
		Two-layer heave plates configuration	3.45	-4.06	0.09	0.88	7.29	-7.17	-0.74	1.90
Yaw	deg	Single-layer heave plate configuration	0.30	-0.74	-0.24	0.16	1.61	-3.12	-0.42	0.71
		Two-layer heave plates configuration	0.62	-0.55	0.11	0.17	2.29	-2.22	0.15	0.59

Fig. 16 Comparison of the RAOs of heave motion for the single-layer heave plate and two-layer heave plate configurations

Fig. 17 Comparison of time series of heave motion response for a single-layer heave plate and two-layer heave plate configurations in the one-hundred-year return sea state.

It is indicated in Table 12 that the octagonal FDPSO with a single-layer heave plate configuration has smaller motion response amplitude than that of two-layer heave plate configuration. The RAO comparisons in Fig. 16 and time series comparisons of heave motions in Fig. 17 both validate this conclusion. From this point of view, it can be summarized that the single-layer heave plate configuration has better hydrodynamic characteristics than that of the two-layer heave plate configuration. However, it should be pointed out that this summary is only valid for hydrodynamic concerns. If some other aspects were instead considered, such as the structural arrangement and fatigue strength, the two-layer heave plate configuration might be more advantageous, for it can maintain a much better structural health condition. But they are not included in the study of this paper.

7 Conclusions

The influence of various heave plate configurations on an

octagon FDPSO has been investigated in this paper through numerical simulation and model testing methodologies. The following conclusions can be drawn from this study.

(1) The heave motion response of the FDPSO can be reduced by increasing the diameter of the heave plates, but the wave-induced-load must be considered under severe sea states.

(2) The difference of heave motion response due to the variance of draft depths of the single heave plate is minimal.

(3) The large spacing value between two layers of the heave plates benefits the heave response of the FDPSO to some extent, but wave-induced-load restricts the application of the two large spacing design, for the upper heave plate may undertake a large wave force under severe sea states.

(4) For the reference octagon FDPSO, the single-layer heave plate configuration has better hydrodynamic performance than that of the two-layer heave plate configuration. Nevertheless, from the view point of structural arrangement and fatigue strength, some different choices can also be made.

The research contained in this paper is focused on the influence of various heave plate configurations on the heave motion response for an octagonal FDPSO. Further studies may be performed using perforated heave plates or differing under-water geometries of a platform with variable cross-sections.

References

- Harris, W. D., Howard, H. J., Hampshire, K. C., Moore, J. A., Bayne, K. J., & Pepin-LeHalleur, J. . 2010. FDPSOs: The New Reality, and a Game-Changing Approach to Field Development and Early Production System. *Offshore Technology Conference*, Houston, Texas. DOI: 10.4043/20482-MS
- Haslum H A, Faltinsen O M, 1999. Alternative shape of spar platforms for use in hostile areas. *Offshore Technology Conference*, Houston, Texas. DOI: 10.4043/10953-MS
- Li Y C, Cheng L, Thiagarajan K. 1999. Numerical estimation of hydrodynamic heave damping of a vertical cylinder with appendages. *The ninth International Offshore and Polar Engineering Conference*. ISOPE-I-99-297. Brest, France.
- Tao L, Lim K Y, Thiagarajan K. 2004. Heave response of classic spar with variable geometry. *Journal of Offshore Mechanics and Arctic Engineering*, 126(1), 90-95.
- Prislin I, Blevins R D, Halkyard J E. 1998. Viscous damping and added mass of solid square plates. *17th International Conference on Offshore Mechanics and Arctic Engineering*, Lisbon, Portugal.
- Tao, L., Molin, B., Scolan, Y. M., Thiagarajan, K. .2007. Spacing effects on hydrodynamics of heave plates on offshore structures. *Journal of fluids and structures*, 23(8): 1119-1136. DOI: 10.1016/j.jfluidstructs.2007.03.004
- Downie, M. J., Graham, J. M. R., Hall, C., Incecik, A., Nygaard, I. 2000. An experimental investigation of motion control devices for truss spars. *Marine structures*, 13(2): 75-90. DOI: [https://doi.org/10.1016/S0951-8339\(00\)00010-1](https://doi.org/10.1016/S0951-8339(00)00010-1)
- Shen W, Tang Y, Liu L. 2012. Research on the hydrodynamic characteristics of heave plate structure with different form

- edges of a spar platform. *China Ocean Engineering*, 2012(26): 177-184.
- Zhang, F., Yang, J. M., Li, R. P., Hu, Z. Q. 2006. Effects of heave plate on the hydrodynamic behaviors of cell spar platform. *American Society of Mechanical Engineers*, OMAE2006-92199: 203-209. DOI: 10.1115/OMAE2006-92199, Hamburg, Germany.
- Tao L, Dray D. 2008. Hydrodynamic performance of solid and porous heave plates. *Ocean Engineering*, 35(10): 1006-1014. DOI: 10.1016/j.oceaneng.2008.03.003
- Li, J., Liu, S., Zhao, M., Teng, B. 2013. Experimental investigation of the hydrodynamic characteristics of heave plates using forced oscillation. *Ocean Engineering*, 2013(66): 82-91. DOI: 10.1016/j.oceaneng.2013.04.012
- Lavrov A. and Soares C. 2016. Modelling the heave oscillations of vertical cylinders with damping plates. *International Journal of Maritime Engineering*, Trans RINA, 2016. Vol 158, Part A3: A187-A197.
- Lopez-Pavon C, Souto-Iglesias A. 2015. Hydrodynamic coefficients and pressure loads on heave plates for semi-submersible floating offshore wind turbines: A comparative analysis using large scale models. *Renewable Energy*, 2015,(81): 864-881. DOI: 10.1016/j.renene.2015.04.003
- Philip N T, Nallayarasu S, Bhattacharyya S K. 2013. Experimental investigation and CFD simulation of heave damping effects due to circular plates attached to spar hull. *Ships and Offshore Structures*, 2013: 1-17. DOI: 10.1080/17445302.2013.835146
- Garrido-Mendoza, C A, Thiagarajan, K. P., Souto-Iglesias, A., Colagrossi, A., Bouscasse, B., 2015. Computation of flow features and hydrodynamic coefficients around heave plates oscillating near a seabed. *Journal of Fluids and Structures* 2015 (59): 406-431. DOI: 10.1016/j.jfluidstructs.2015.10.003
- Lee C, Newman J N. 2005. Computation of wave effects using the panel method. *Numerical Models in Fluid Structure Interaction*, 2005(42): 211-251. DOI: 10.2495/978-1-85312-837-0/06
- DNV, 1993, SESAM User's Manual-WADAM, Det Norske Veritas.
- DNV, 2005, SESAM User's Manual-DeepC, Det Norske Veritas.
- Rho, J. B., Korobkin, A. A., Jung, J. J., Shin, H. S., Lee, W. S. 2007. Coupled analysis of deepwater floating system including VIV in time domain. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*, California, USA :639-649. DOI: 10.1115/OMAE2007-29523
- Lu H N, Yang J, Peng T. 2006. *Research on parameters of perforated wall in current generation system of deepwater offshore basin*. Journal of Hydrodynamics (Ser. A), 2006(2): 006.
- Stansberg C T, Ormberg H, Oritsland O. 2002. Challenges in deep water experiments: hybrid approach. *Journal of Offshore Mechanics and Arctic Engineering*, 124(2): 90-96. DOI: 10.1115/1.1464129
- Ward, G., Hansen, V. L., Kim, M. H., Wang, L. 2004. Model-the-model: validating analysis models for deepwater structures with model tests. 1144 – 1152. *Offshore Technology Conference*. Houston, USA. DOI: 10.4043/16586-MS
- Su Y, Yang J, Xiao L 2009. Hybrid Verification of a Deepwater Cell-Truss Spar. *China Ocean Engineering*, 23(1):1-14.
- Fan, T, Qiao, D, Ou, J, 2014. Dynamic Effects of Equivalent Truncated Mooring Systems for a Semi-submersible Platform. *Brodogradnja* 65 (4): 35-51.
- Tao L, Thiagarajan K. 2003. Low KC flow regimes of oscillating sharp edges I. Vortex shedding observation. *Applied Ocean Research*, 25(1): 21-35. DOI: 10.1016/S0141-1187(03)00031-2
- Tao L, Thiagarajan K. 2003. Low KC flow regimes of oscillating sharp edges. II. Hydrodynamic forces. *Applied Ocean Research*, 25(2): 53-62. DOI: 10.1016/S0141-1187(03)00046-4
- Thiagarajan, K. P., Datta, I., Ran, A. Z., Tao, L., Halkyard, J. E. 2002. Influence of heave plate geometry on the heave response of classic spars. *21st International Conference on Offshore Mechanics and Arctic Engineering*, Oslo, Norway:621-627. DOI: 10.1115/OMAE2002-28350
- Tao L, Cai S. 2004. Heave motion suppression of a Spar with a heave plate. *Ocean Engineering*. 31(5): 669-692. DOI: 10.1016/j.oceaneng.2003.05.005

基于不同垂荡板结构形式的八角形深水 FDPSO 垂荡运动响应研究

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