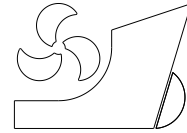


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<http://dx.doi.org/10.21278/brod68207>

ISSN 0007-215X
eISSN 1845-5859

PARAMETRIC STUDY ON THE HYDRODYNAMIC RESPONSE OF DSI POLYGONAL SHAPED FPSO

UDC 629.5.015.2:629.51:629.5.018.1:502.087

Original scientific paper

Summary

In the present paper, numerical investigations was carried out on a 1:45 scaled model of DSI nine sided polygonal non-ship shaped FPSO, by varying different parameters of the model. Parameters such as inlet pipe radius, and moonpool radius was considered for the study and the variation of the RAO in surge and heave were plotted and reported in the present paper. Previously, experiment were conducted by the author on a 1:45 scale DSI nine sided polygonal non-ship shaped FPSO model with three different mooring arrangements viz. 100% turret mooring, 50% vessel and 50% turret mooring, and 100% vessel mooring. Author also conducted experiments on the model with different sizes of damping plates attached at the keel and skirt portion of the model to study its influence on the responses of the vessel and comparison was made with numerical result obtained from Wave analysis, MIT (WAMIT) software. Numerical study was carried out in WAMIT on the scaled model and the results were compared with those obtained from model tests in the wave basin.

Key words: FPSO, Turret mooring, damping plate, DSI Non ship shaped FPSO, keel plate, skirt plate. Inlet pipe radius, moonpool radius

1. INTRODUCTION

Floating, Production, Storage and Offloading systems (FPSO) are increasingly competitive to the traditional deepwater production solutions, e.g., SPAR, TLP and semi submersible in the current offshore oil and gas environment. Today oil and gas industry is looking for environmentally challenging technologies for their large production fields in deep water as well as in arctic environment. In such situation need for an FPSO suitable for harsh environments, and deepwater location arises. A new design of a non-ship shaped FPSO, developed by Deepwater Structures Inc. (DSI), Houston, Texas catering to the icy waters of the arctic as well as severe sea states of the North Sea is taken for the study.

Many researchers have studied the dynamic characteristics of ship shaped and Non ship shaped FPSO in winds and currents using numerical and experimental methods. Thiagarajan et al. [9] carried out numerical simulations and model testing to identify the influence of a heave plate on the heave response of the spar. Masetti et al. [7] carried out experiments to study the influence of different skirts on the response of monocolumn floating production structure and the influence of variation of the external diameter along the vertical axis. Torres et al. [11] published works by changing the internal geometry of the moonpool. Changes of the moon pool internal geometry modified the behaviour of vertical oscillation of the water inside the moonpool. Vijayalakshmi et al. [12] presented experiments results on 1:45 non-ship shaped FPSO model for three different mooring configurations and for FPSO models with and without damping plates. The effect of mooring configurations in the heave response of the FPSO and the effect of damping plates in the heave and pitch responses of the FPSO under regular waves was investigated. The DSI non ship shaped FPSO was numerically modeled with moon pool and without moon pool and the effect of moon pool on the response of the structure was studied by Vijayalakshmi et al. [13].

Goncalves et al. [3] developed a mathematical model of monocolumn floating production structure to estimate the first order heave and pitch motions of the platform. Experimental tests were carried out in order to calibrate this model. The response of each body was estimated numerically using the WAMIT code. Fan et al. [2] proposed an octagonal FPSO for oil and gas development in shallow waters. Goncalves et al. [4] conducted experimental study on Vortex Induced motion (VIM) for monocolumn platform. Shen et al. [8] studied the hydrodynamic characteristics of heave plates for Truss Spar; Experiments were conducted by Vijayalakshmi et al. [14] to study the hydrodynamic response of the DSI FPSO vessel on a 1:45 scale model with damping plates (skirt plate and keel plates). Bin et al. [1] numerically studied the damping effects on the Mathieu instability and the mechanism of Deep draft multi-spar (DDMS), a novel deepwater platform. Koh and Cho [5] studied the effect of heave plates at the bottom of the cylinder. The heave plate attached at the bottom of the cylinder had a distinct advantage in reducing the motion responses of a floating circular cylinder by increasing added mass and damping coefficient. The aim of the present work is to study the Hydrodynamic response of DSI non-ship shaped FPSO, catering to the icy waters of the arctic environment.

1.1. Non ship shaped vessel

DSI non-ship shaped FPSO has a monolithic non ship-shaped hull of polygonal configuration surrounding a central double tapered conical moon pool and contains water ballast and oil storage compartments. The exterior side walls of the hull have flat surfaces and sharp corners to cut ice sheets, resist and break ice, and move ice pressure ridges away from the structure. An adjustable water ballast system induces heave, roll, pitch and surge motions of the vessel to dynamically position and manoeuvre the vessel to accomplish ice cutting, breaking and moving operations. The moon pool shape and other appendages on the vessel provide added virtual mass capable of increasing the natural period of the roll and heave modes. It reduces dynamic amplification and the chance of resonance due to waves and vessel motion. This also facilitates manoeuvrability of the vessel. The vessel may be moored by a disconnectable turret buoy received in a support frame at the bottom of the moon pool and to which flexible well risers and mooring lines are connected. The cross sectional view, of the DSI FPSO showing all the features, including inlet opening and moonpool details is shown in Fig.1.

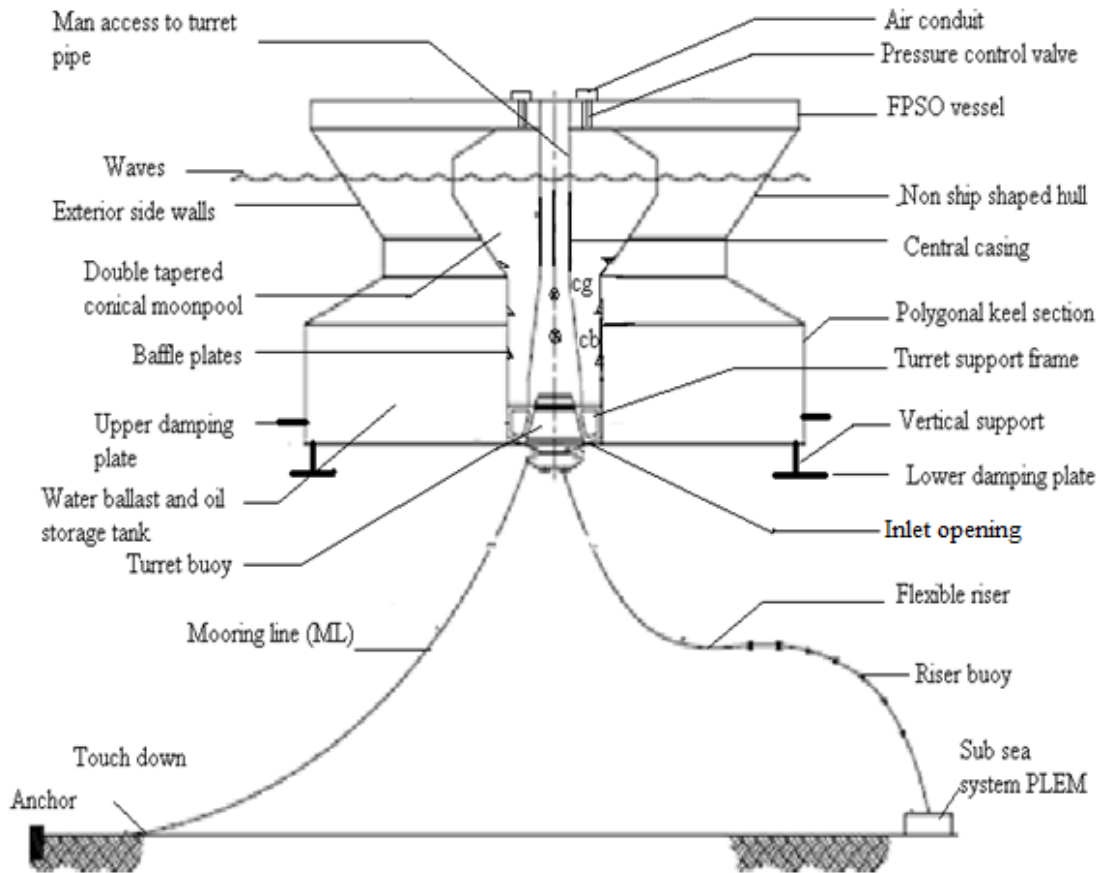


Fig.1. Sectional View of DSI FPSO Vessel

A 1:45 scale model of the DSI non-ship shaped FPSO was fabricated for the experimental study. The FPSO has a maximum diameter of 100m and height of 55.5m and is envisaged to cater in icy waters where the water depth is 135m. Draft of the structure is 43.2 m. The vertical center of gravity and vertical center of buoyancy are 25.56m and 17.59m, respectively. The parameters of the DSI FPSO are given in Table 1. The special feature of this FPSO is that it is capable of withstanding large ice loads. The type of ice in the arctic sea, its strength and the load on the vessel due to wind and current are highly stochastic and complex in nature. Keeping the above facts in mind the DSI-FPSO vessel was designed to face such harsh environment and the associated loads, rather than escape from it. The key design features are: a rigid floating structure with a large mass, a large lever arm and an ideal ice breaking slope at the ice contact face.

1.2 Ice-Breaking Capacity of the Vessel

The vessel may be moored with a corner facing the predominant drift moving direction of ice floes. The uneven sided polygonal shape of the hull induces flexural failure of ice. Flexural failure is also induced by pitching motion of the vessel, which can be achieved by changing water levels in the ballast tanks. The broken pieces of ice ride down on the slope of the vessel, and finally clear around it. The schematic diagram of ice breaking by the vessel is shown in Fig.

2. The experimental model without damping plates and with damping plates, fabricated at Indian institute of technology – Madras used for the study is shown in Fig.3. and Fig.4.

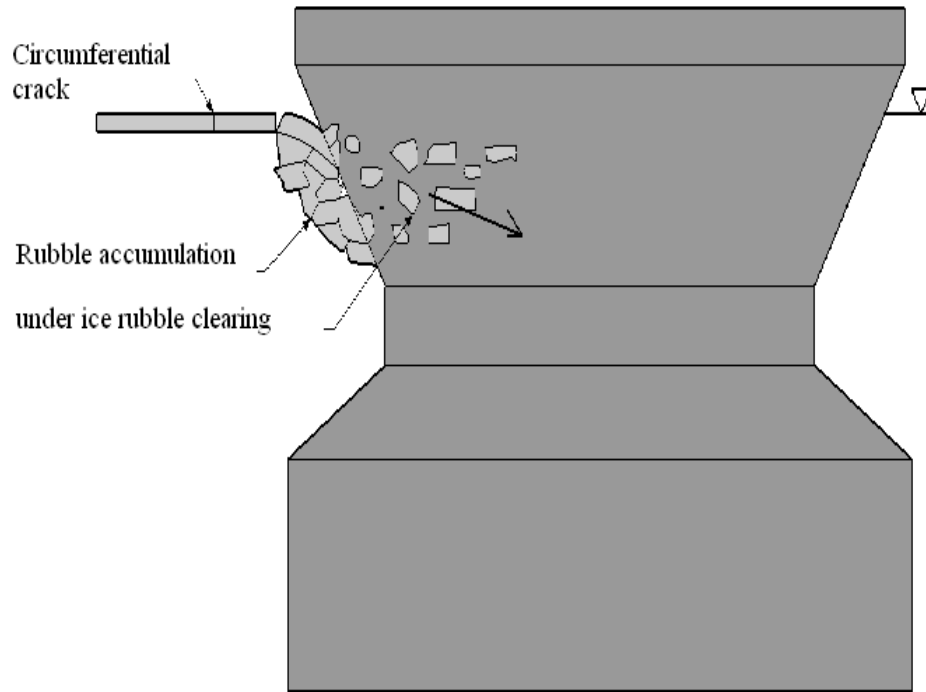


Fig.2 Schematic view of ice breaking by DSI FPSO (courtesy by Deep Water Structure Inc. (DSI))



Fig.3 Model without damping plate



Fig.4 FPSO model with damping plates

Table 1 Parameters of DSI FPSO

Parameter	Prototype	Model (1:45)
Weight (W)	2495×10^3 kN	27.38 kN
Freeboard	12.3 m	0.27 m
Water depth (d)	135 m	3.0 m
Height of hull	55.5 m	1.23 m
Diameter of hull (B)	100.8 m	2.24 m
Center of gravity (KG)	25.56 m	0.568 m
Center of buoyancy (KB)	17.59 m	0.39 m
Radius of Gyration R_{xx}	25.29 m	0.56 m
R_{yy}	25.29 m	0.56 m
R_{zz}	24.87 m	0.55 m
Meta-center (GM)	1.6 m	0.035 m

2. NUMERICAL STUDY

An accurate and efficient computational analysis of wave-body interaction is important in the design of offshore structures and marine vessels. Among various numerical approaches, panel method, a kind of boundary element method, is widely used for the numerical prediction of response of offshore structures. WAMIT (Wave Analysis at Massachusetts Institute of Technology) is a radiation diffraction program developed for the analysis of the interaction of surface waves with offshore structure. Torres et al [10] carried out numerical investigation to study the application of moonpool in monocolumn. Malta et al [6] studied the effect of moonpool in monocolumn floaters with numerical methods (WAMIT) to emphasize the differences caused with 2 different hull geometries.

The non ship shaped FPSO vessel on which the experiments were conducted was modeled using WAMIT higher order panel method. The advantage of panel method is that the problem is reduced to a two-dimensional problem instead of a three dimensional problem. Parametric study was carried out for the following models

- FPSO with 0.1 m keel and 0.1 m skirt plate (FPSO K1S1)
- FPSO with 0.2 m keel and 0.1 m skirt plate (FPSO K2S1)
- FPSO with 0.3 m keel and 0.1 m skirt plate (FPSO K3S1)

2.1. Modeling of geometry using Multisurf

Multisurf is a computer aided design (CAD) package for parametric design of 3D geometric objects involving free form curves and surfaces. The model surface is subdivided into

patches, each is a smooth continuous surface, and the ensemble of all patches represents the complete body surface. In order to provide the accuracy of each patch, a set of small elements are defined which are called panels. These panels are curved surfaces in physical space. Depending on the accuracy requirements these panel size can be modified in the Multisurf. It is required to prepare only the submerged portion of the FPSO in Multisurf. The total draft of the FPSO is 0.97 m and the clearance between deck and sea water level is 0.14m. With these details the geometry of the submerged portion was developed in Multisurf which is shown in the Fig. 5. From Multisurf, the geometric data file was generated and imported to WAMIT. Panel size of 0.03 m was used for the analysis. The outer hull and wetted surface of the moonpool was modeled using WAMIT.

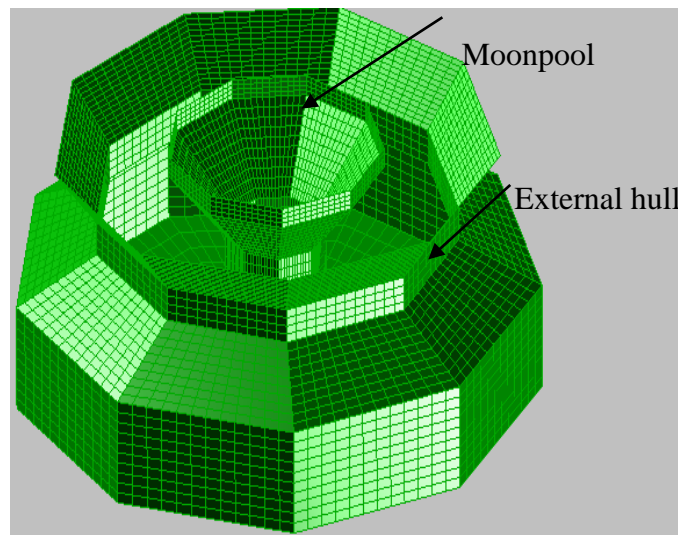


Fig.5. Multisurf model of DSI FPSO

The damping in WAMIT analysis is produced by radiation of waves and by the oscillatory viscous drag force. Viscous damping which plays an important role in the resonant response was empirical input to the analysis and is not explicitly calculated. The external damping matrix can be given as input in WAMIT, the details of which are available in WAMIT user manual. The numerical analysis was carried out for ω^* ($\omega^* = \omega^2 B/2g$); (B -Diameter of the FPSO) range from 1.97 to 0.28.

2.2 . Formulation of external damping and Stiffness matrix

With the input files generated the numerical analysis of non ship shaped FPSO model was carried out for wave period ranging from 1.5 s to 4 s at an increment of 0.2 s. The heave RAO obtained from WAMIT for FPSO without damping plate is of 7.8 m/m at the natural heave period of 2.85 s and does not match with the peak heave RAO from experiments. The prototype heave natural period is 19 s and is close to the peak of wave spectrum and can cause resonance. In obtaining the peak values of heave RAO the damping values are important. WAMIT considers only radiation damping of the body and the damping ratio ξ is obtained as follows:

$$\xi = \frac{B_{33}}{(2(\Delta + A_{33})\omega_n)} = 1.35 \% = 0.0135, \text{ where the heave damping, } B_{33} = 0.194 \text{ t-rad/s,}$$

mass, $\Delta = 0.29 \text{ t}$, added mass in heave, $A_{33} = 2.95 \text{ t}$, correspond to the natural frequency, $\omega_n = 2.2 \text{ rad/sec}$ (natural period of 2.85 sec). In other words, the heave radiation damping (ξ) considered by WAMIT is 0.0135 and hence at this damping level the results of WAMIT severely overestimates the motion response in heave as compared to those from experiments. The measured heave damping in the model is 0.102 from the free heave vibration test. Using the provision to input dimensional external damping in WAMIT by the user, the experimentally obtained damping has been input to WAMIT. The additional hydrodynamic damping values input to WAMIT analysis is tabulated in Table 2.

Table 2 Additional hydrodynamic damping input to WAMIT

FPSO model	Natural frequency f_h (Hz)	Damping ratio from experiment (regular wave test RAO) (ζ_3)%	Hydrodynamic added mass from WAMIT A_{33} (t)	Hydrodynamic damping from WAMIT B_{33} (t-rad/s)	Additional hydrodynamic damping input to WAMIT B_{33} (t-rad/s)
FPSO without plate	0.354	10.2	2.95	0.194	1.26
FPSO K1S1	0.33	14.3	4.32	0.766	1.96
FPSO K2S1	0.32	16.3	4.92	0.899	2.51
FPSO K3S1	0.31	19.6	5.53	1.07	3.35

The mooring lines cannot be modeled in WAMIT, so in order to include the effect of mooring, external mooring stiffness matrix was included in WAMIT. Turret mooring was adopted in numerical simulation. The stiffness coefficient was derived based on the differential changes of mooring line tension caused by the static motion of the floating body. Similar procedure was adopted to form the stiffness matrix and input in WAMIT.

2.3. Experimental and numerical comparisons

Surge added mass (A_{11}) and damping coefficient (B_{11}) does not show any variation with the addition of damping plates. Heave added mass (A_{33}) increases with the increase in the maximum diameter of the vessel. As the size of keel plate is increased the added mass and the corresponding damping coefficient (B_{33}) also increases. The pitch added mass also follows the same trend as that of heave added mass. The pitch added mass (A_{55}) increase with the increase in

the maximum diameter of the vessel. But the pitch damping coefficient follows a different trend. The graph showing the variation of added mass and Damping coefficient values is included in our previous publications [12]

The experimental and numerical comparison of the heave RAO of FPSO with three different widths of keel plates and 0.1 m wide skirt plate, and without damping plate (FPSO) obtained from the experiments is shown in Fig. 6. For all the above model variation, the numerical prediction is found to be good. The heave peak frequency shifts towards higher frequency with the addition of keel and skirt plates. The peak heave RAO occurred at $\omega^* = 0.56$, 0.61, 0.71 and 0.71 for FPSO without damping plate, FPSO with 0.1m wide keel 0.1 m wide skirt plate, FPSO with 0.2m wide keel 0.1 m wide skirt plate and FPSO with 0.3m wide keel 0.1 m wide skirt plate, respectively. The maximum RAO of FPSO K1S1 is 1.67 m/m @ $\omega^* = 0.61$, which is significantly lower than for FPSO without damping plate of the order of 38.83 %. The maximum heave RAO for the FPSO K2S1 model is 1.59 m/m @ $\omega^* = 0.71$; and for the FPSO K3S1 model is 1.27 m/m @ $\omega^* = 0.71$. Compared to FPSO without damping plate, the reduction in maximum heave response magnitude is 41.76 % and 53.48 % for FPSO K2S1 and FPSO K3S1, respectively. The reduction in maximum RAO with the addition of keel and skirt plates is due to the increase of damping.

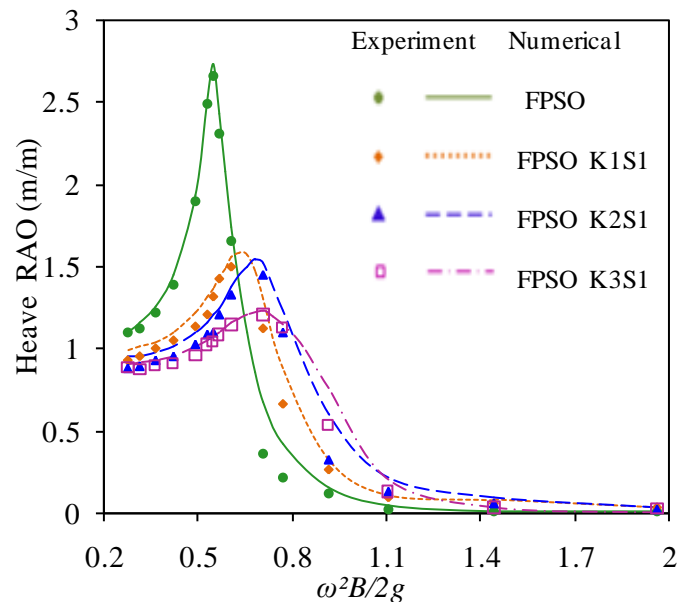


Fig. 6 Comparison of heave RAO for FPSO with different width of keel and skirt plate

3. PARAMETRIC STUDY

Case study was carried out by changing the radius of the inlet opening, and moonpool area. The study was carried out numerically for three models namely FPSO K1S1, FPSO K2S1 and FPSO K3S1. Radius of inlet pipe and moonpool in the basic model are 0.2m and 0.5m, respectively. First parametric study was carried out by varying the inlet pipe radius from 0.3 to 0.5m and the moon pool radius was kept as constant 0.5m. Second parametric study was carried out by varying the Moonpool radius from 0.2 to 0.8m and the inlet radius was kept as constant

0.2 m. The different combinations of inlet pipe and moonpool radius adopted are given in Table 3. Multisurf model of FPSO K1S1 with 0.3 and 0.5m inlet radius is shown in Fig.7 and Fig.8 respectively. The Multisurf model and input files are generated, then the WAMIT analysis has been carried out and the response of the model was evaluated. The salient results and discussion of the parametric study are discussed below.

Table 3 combinations of inlet and moon pool opening

PARAMETRIC STUDY			
FPSO WITH DIFFERENT INLET RADIUS (FPSO K1S1, FPSOK2S1, FPSO K3S1)		FPSO WITH DIFFERENT MOONPOOL RADIUS (FPSO K1S1, FPSOK2S1, FPSO K3S1)	
Radius of inlet	Radius of Moon pool	Radius of inlet	Radius of Moon pool
0.2 m	0.5 m	0.2 m	0.2 m
0.3 m	0.5 m	0.2 m	0.3 m
0.4 m	0.5 m	0.2 m	0.4 m
0.5 m	0.5 m	0.2 m	0.5 m
		0.2 m	0.6 m
		0.2 m	0.7 m
		0.2 m	0.8 m

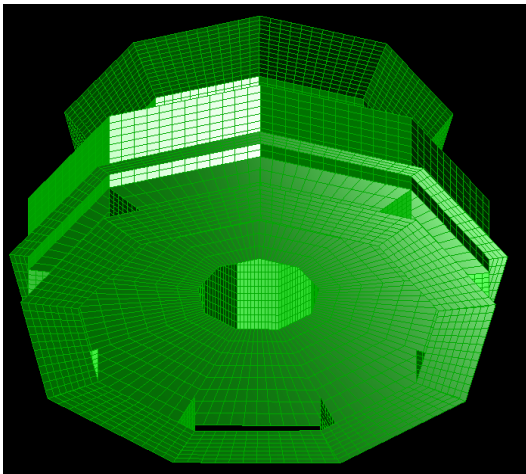


Fig. 7 FPSO with 0.3m inlet radius

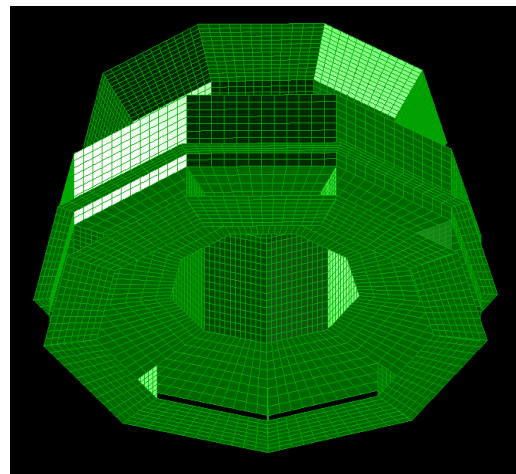


Fig. 8 FPSO with 0.5m inlet radius

4. RESULT AND DISCUSSION

4.1 Inlet radius

Parametric study was carried out for FPSO model fitted with different width of keel and skirt plates for four different inlet pipe radii ranging from 0.2m to 0.5m using WAMIT. The variation of surge and heave RAOs of FPSO with different inlet radius are discussed below.

4.1.1 FPSO K1S1 model with different inlet radius

The surge RAOs for FPSO K1S1 with inlet radius varying from 0.2m to 0.5m is shown in Fig.9.(a). The surge RAO decreases with the increase in wave frequency and there is no significant difference in surge RAO for different radius of inlet pipe. The surge RAO varied from 0.2 to 0.86 for the ω^* ($\omega^* = \omega^2 B/2g$); (B -Diameter of the FPSO) range from 1.97 to 0.28.

The heave RAOs for FPSO K1S1 with inlet radius varying from 0.2m to 0.5m is shown in Fig.9.(b) FPSO K1S1 with 0.4 m inlet opening produces a maximum of 61.17 % reduction in the maximum heave RAO when compared to FPSO model without damping plate. For the other two cases namely, 0.3 m and 0.5 m inlet radius, the reduction in maximum heave RAO is about 41.76 % and 39.56 %, respectively. Secondary peak is observed in FPSO K1S1 model with 0.3m inlet radius, which may be due to the effect of multiple frequencies. The heave RAO and the heave natural frequency for FPSO K1S1 model with 0.2m inlet radius and 0.5m inlet radius are nearly the same. These observations lead to the conclusion that as the radius of the inlet pipe increases, the amount of water entrapped inside the pipe is increased and this in turn increases the damping in the system up to a certain limit of entrapped water.

The comparison of predicted pitch RAO with experiments is not satisfactory and hence not included in the following sections.

4.1.2 FPSO K2S1 model with different inlet radius

The surge RAOs for the FPSO K2S1 with inlet radius varying from 0.2m to 0.5m is shown in Fig. 10.(a). The surge RAO decreases with the increase in wave frequency and there is no significant difference in surge RAO for different radius of inlet pipe. The surge RAO varied from 0.2 to 0.86 for the frequency (ω^*) range from 1.97 to 0.28.

The heave RAOs for FPSO K2S1 with inlet radius varying from 0.2m to 0.5m is shown in Fig. 10. (b). FPSO K2S1 with 0.2 m and 0.3 m inlet opening produces a maximum of 41.76 % reduction in the maximum heave RAO when compared to FPSO model without damping plate. For the other two cases namely, 0.4 m and 0.5 m inlet radius, the reduction in maximum heave RAO is about 41.39 % and 41.03 %, respectively. Secondary peaks are observed for FPSO K2S1 model with 0.3m and 0.4m inlet radius, which may be due to the effect of multiple frequencies.

4.1.3 FPSO K3S1 model with different inlet radius

The surge RAOs for FPSO K3S1 with inlet radius varying from 0.2m to 0.5m is shown in Fig.11.(a). The surge RAO decreases with the increase in wave frequency and there is no significant difference in surge RAO for different radius of inlet pipe. The surge RAO varied from 0.2 to 0.86 for the ω^* range from 1.97 to 0.28.

The heave RAOs for FPSO K3S1 with inlet radius varying from 0.2m to 0.5m is shown in Fig. 11.(b). as the radius of the inlet pipe is increased from 0.2m to 0.5m, the heave RAO is reduced. FPSO K3S1 with 0.5m inlet opening produces a maximum of 60.81 % reduction in heave RAO, when compared to FPSO without damping plate. For the other three cases, namely 0.2 m, 0.3m and 0.4m inlet radii, the reduction in heave RAO is about 53.48%, 56.04% and 60.44 %, respectively. These observations lead to the conclusion that as the radius of the inlet pipe increases, the amount of water entrapped inside the pipe is increased and this in turn increases the damping in the system up to a certain limit of entrapped water. The maximum heave and pitch RAOs for FPSO model with different keel and skirt plates and with different inlet radius are given in Table 4.

Based on the parametric study carried out with respect to different inlet radii, the following conclusions are drawn:

- There is no significant difference in surge RAO for different radius of inlet pipe.
- FPSO K1S1 with 0.4m inlet opening is found to produce the least heave RAO of about 61.17 % less when compared to FPSO without damping plate (Heave RAO = 2.73 m/m) [7]
- Compared to FPSO K3S1 model, FPSO K1S1 model can be effectively used with 0.4m inlet opening, which produces the lesser heave RAO.
- The variation in heave RAOs for FPSO K1S1 and FPSO K2S1 with 0.2 m and 0.5 m radius inlet opening is insignificant.

4.1 Moonpool radius

Parametric study was carried out for FPSO model fitted with different width keel and skirt plates for seven different moon pool radius ranging from 0.2 m to 0.8 m. The results of the parametric study are discussed below.

4.2.1 FPSO K1S1, FPSO K2S1 and FPSO K3S1 models with different moonpool radius

The surge RAOs for the FPSO K1S1, FPSO K2S1 and FPSO K3S1 obtained from WAMIT for different moon pool radius are shown in Figs. 12(a-c). The surge RAO decreases with the increase in wave period and there is no significant difference in surge RAO for different radius of moonpool for all the three FPSO models. The heave RAOs for FPSO K1S1, FPSO K2S1, and FPSO K3S1 obtained from WAMIT for different moonpool radius are shown in Figs. 13 (a-c). There is no significant difference in heave RAO for different radius of moonpool for all the three FPSO models.

Based on the parametric study carried out with respect to different moonpool radius, the following conclusions are drawn: There is no significant difference in surge RAOs for different moon pool radius of FPSO. However the heave RAO's showed a marginal difference for the wave period near the resonant period.

Table 4 Peak heave RAO for FPSO with different inlet radius

	RAO		
FPSO model		Heave RAO (m/m)	
FPSO K1S1	0.2m radius	1.67(38.83 % ↓)	
	0.3m radius	1.59 (41.76 % ↓)	
	0.4m radius	1.06 (61.17 % ↓)	
	0.5m radius	1.65 (39.56 % ↓)	
FPSO K2S1	0.2m radius	1.59 (41.76 % ↓)	
	0.3m radius	1.59 (41.76 % ↓) (secondary peak @ 2 sec)	
	0.4m radius	1.6 (41.39 % ↓) (secondary peak @ 2 sec)	
	0.5m radius	1.61 (41.03 % ↓)	
FPSO K3S1	0.2m radius	1.27 (53.48 % ↓)	
	0.3m radius	1.20 (56.04 % ↓)	
	0.4m radius	1.08 (60.44 % ↓)	
	0.5m radius	1.07 (60.81 % ↓)	
FPSO without Damping plate	0.2 m inlet 0.5 m moonpool	2.73	

5. CONCLUSION

Inlet opening plays a major role in response of the vessel, increasing the inlet opening to 0.5m reduces the pitch RAO by 7% , 17% and 10% for FPSO with K1S1, K2S1, K3S1 respectively. FPSO (K1S1) with 0.4m inlet opening (10 HS) is found to produce the least heave RAO when compared to all other case. Hence, instead of using 30 cm heave and 10 cm skirt plate, 10 cm keel plate and 10 cm skirt plate can be effectively used with 0.4m inlet opening. Therefore the material cost can be reduced. Change in the moonpool opening does not produces major change in the surge and heave response of the vessel.

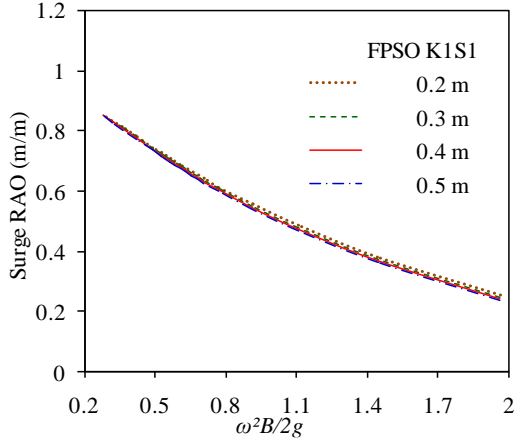


Fig.9 (a)

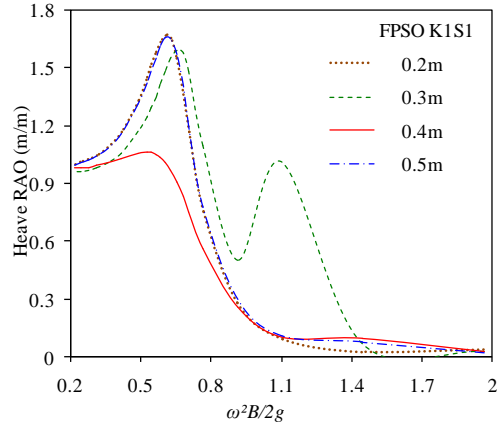


Fig.9 (b)

Fig.9 Surge and heave RAO for FPSO K1S1 model with different inlet radii

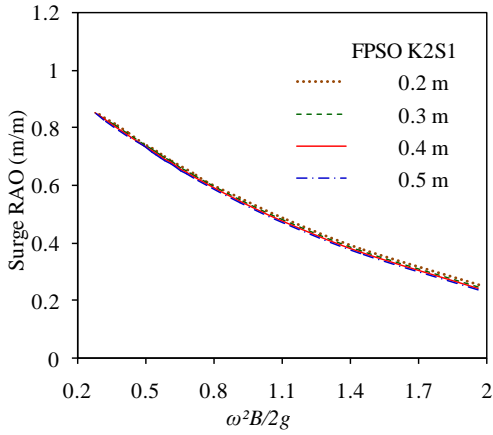


Fig.10 (a)

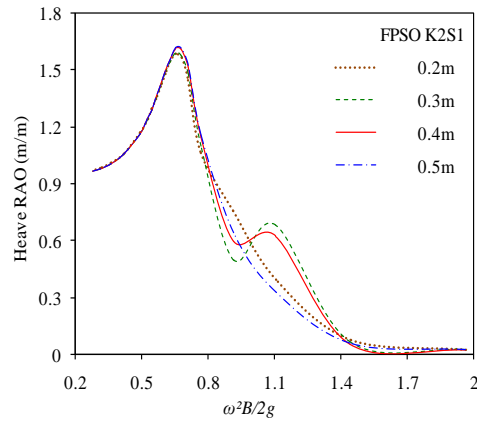


Fig.10 (b)

Fig.10 Surge and heave RAO for FPSO K2S1 model with different inlet radius

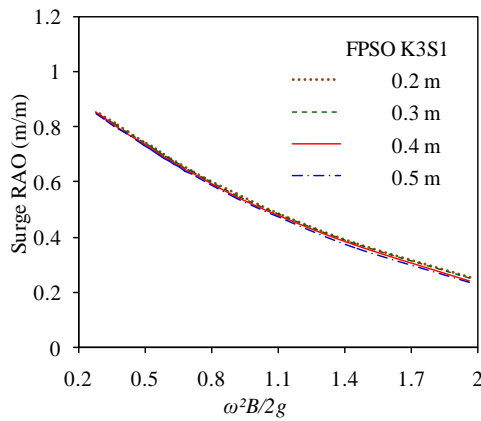


Fig.11 (a)

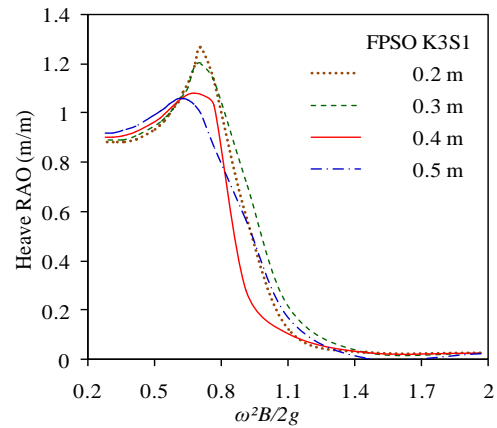


Fig. 11 (b)

Fig.11 Surge and heave RAO for FPSO K3S1 model with different inlet radius

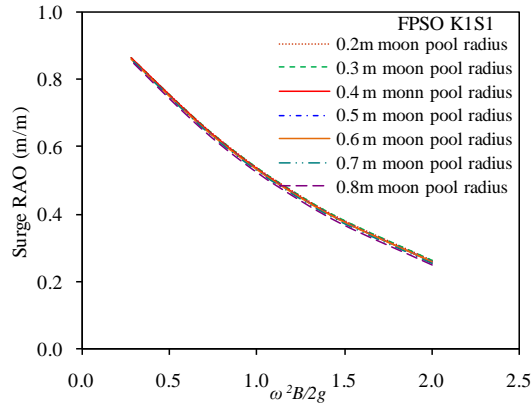


Fig. 12 (a)

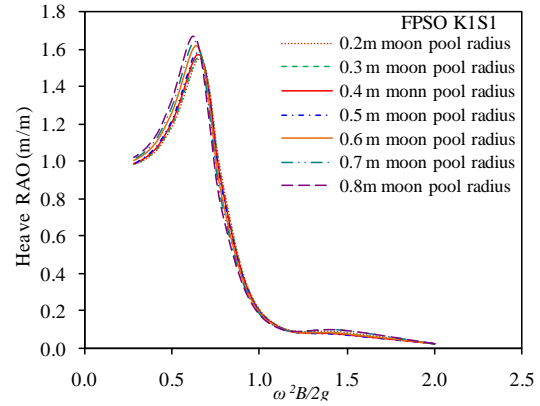


Fig. 13(a)

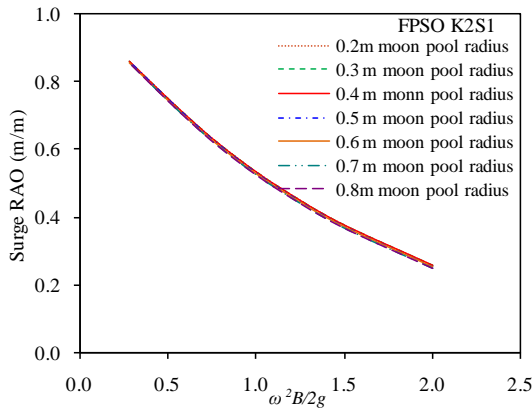


Fig. 12(b)

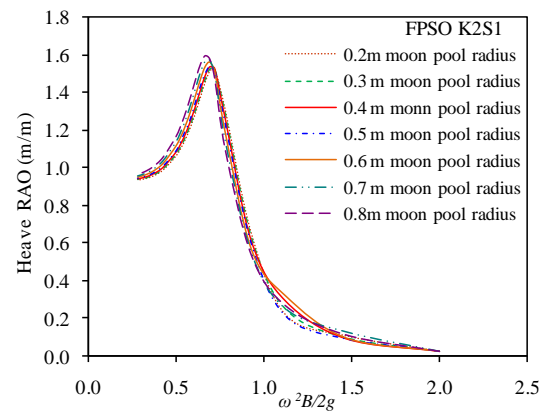


Fig. 13 (b)

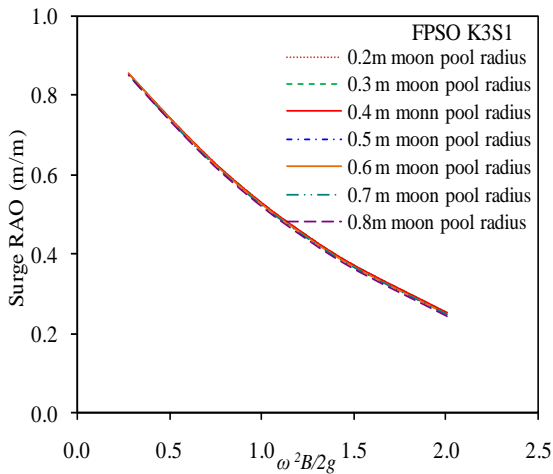


Fig. 12 (c)

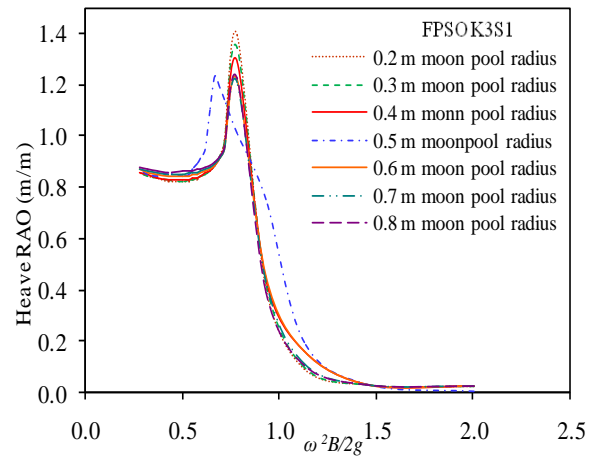


Fig. 13(c)

Fig.12 Surge RAO for FPSO model with
Different moonpool radii

Fig.13 Heave RAO for FPSO
with different moonpool radii

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Accepted: 22.03.2017. Ramanagopal Srinivasan

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