Experimental Investigation on the Influence of Interceptor Plate on the Motion Performance of a Cylindrical FPSO

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In offshore locations with harsh environment, the operation of cylindrical floating production storage and offloading (FPSO) becomes more challenging. Poor motion performance can severely affect the structural safety, mooring system's strength and riser's operation. Therefore, interceptor plate installation above the cylindrical heaveplate is proposed in order to improve FPSO's motion performance especially in heave responses. A set of 1:100 scale model experiments were carried out in the University of Strathclyde's Hydrodynamics Laboratory tank. The main objective of this study is to investigate the influence of the proposed interceptor plate on the motion performance of a cylindrical FPSO for different interceptor plate geometrical parameters such as height and location. The results of this study show that double face interceptor plate installation can reduce the peak responses of heave RAO by about 50% and pitch by about 67% compared to the FPSO model without interceptor plate. Also the fundamental heave and pitch natural frequencies can reduce by about 11% for the same case.

Keywords: Floating production storage and offloading; interceptor; heave plate; motion responses.

1. Introduction

With the continuous development of the offshore oil and gas industry and the trend of exploration into deeper water depth, a significant increase in the use of FPSOs is expected next decade. Due to its symmetrical design and avoidance of complex turret and swivel technology, cylindrical FPSOs were brought into the offshore industry with advantages of simple manufacturing and operation. Sevan Piranema, which was constructed by Sevan Marine Company in 2006 was the first cylindrical FPSO [9]. Beside the common oil and gas application, cylindrical vessels have been widely investigated for different marine applications. Many research works on cylindrical vessels have been performed, such as cylindrical floating breakwater system [12] and renewable energy devices such as wind turbine foundations [13]. Although cylindrical FPSOs provide an economic and flexible approach to production and storage, they can experience significant heave and pitch motion responses especially when operating in harsh environmental conditions. Consequently, the safety and performance of the cylindrical FPSOs can be subject of concern for harsh environment locations.

Many previous works have discussed the improvement of FPSO's motion performance using different designs and techniques. A new anti-heave semi-submersible platform was designed and numerically simulated in both frequency and time domains [10]. Based on comparison analysis in this study, the heave response is greatly reduced with respect to the original platform. Brazilian universities and research institutions have investigated the use of motion-reducing devices such as moonpools, skirts, and beaches to reduce the platform motion [14]. For a cylindrical FPSO designed for the Gulf of Mexico, an experimental investigation on Vortex-Induced Motion was carried out in [15]. Also, the cylindrical FPSO Sevan Piranema's motion behaviour was studied in the context of Brazilian environmental conditions [16]. Pan el al. [17] conducted experimental research on the motion behaviour of a cylindrical platform under random and freak waves.

A new pneumatic platform design to damp the motion was suggested by Cheung et al. [18]. Motion behaviour of the structure with the proposed pneumatic platform was investigated by both numerical and experimental approaches. Experimental study of the hydrodynamic responses of a single floating storage platform with internal fluid tank was performed by Chi et al. [19]. An experimental study on the hydrodynamic performance of a new type of deep draft multi-column FPSO was presented in [20]. Wang et al. [21] presented a new cylindrical FPSO design named "sandglass-type" FPSO. Numerical and experimental studies were conducted in order to examine the performance limits of the new design and compared it with classical ship type [22]. The sandglass-type design improved the hydrodynamic performance of the FPSO significantly [23,24].

Generally, a free floating vessel has six degrees of freedom. According to DNV GL [11], the FPSO ship shape has its natural period of surge, sway and yaw greater than 100s; therefore, these motion responses are far from any wave excitation forces. However, roll, pitch and heave motions could be critical due to their natural period close to wave excitation forces in the region 10 s to 20 s. Based on the symmetrical geometry of cylindrical FPSO, pitch and roll responses could be considered as the same [2]. Therefore, heave motion response is a key parameter factor of interest in the motion behaviour of the cylindrical FPSO.

Recently, installation of external appendage plate surrounding the base of the main hull, named "heaveplate", was used as a heave motion damper. The heaveplate is the key component of any cylindrical platform as it can efficiently improve the heave response by providing additional damping and added mass [26]. Experimental investigation of the hydrodynamical characteristics of the heaveplate was carried out in [26]. Performance of FPSO with damping plate attached at the keel has also evaluated in arctic ice environment [25]. The study found a significant reduction of 12% in the heave motion and 19% pitch motion of the vessel with heaveplate compared to the original vessel. A numerical study was also conducted to study the effect of installing single and double heaveplates on the heave responses of a spar cylinder. The study found that the heave response reduced with increase the heaveplate diameter and the spacing between the two heaveplates [27].

According to the literature review, different passive control techniques have been presented to reduce the motion responses of the cylindrical FPSO. In the present study, a new passive control technique is also proposed by installing an interceptor plate appendage for cylindrical FPSOs. Aiming to evaluate the influence of installation of the proposed interceptor plate on the motion performance of FPSO vessel, experimental test was carried out for different interceptor plate geometrical parameters and arrangements in regular waves. Since the mooring will improve the motion behaviour due to its additional stiffness, free floating cases were considered in this study as worst motion cases.

2. Proposed interceptor plate concept

In high-speed craft application, the trim variation may cause an increase in resistance and instability in planning boats. In order to control vessels trim, the well-known vertical small blade called “interceptor plate”, is used and located at the aft of the vessel [6]. The interceptor plate is different than flap and trim tab in his size and installation. Interceptor is a relatively small vertical blade considered as an aft peak appendage that generates lift force at high speed aiming to reduce boat trim angle. In recent years, interceptor plate has also been successfully used in aerodynamics applications. The interceptor plate blade was felted into airplane wings and missiles to create lift force for attitude control [7].

In this study, the interceptor plate is proposed to be used in a new marine application by adding it onto the heaveplate of cylindrical FPSO in order to improve the heave and pitch motion responses. The proposed interceptor plate shape is shown in Figure 1. Since the location of the interceptor plate is an important key parameter, different position arrangements are proposed to investigate, namely, upper, lower, and double face interceptor plate configurations, as shown in Figure 2.

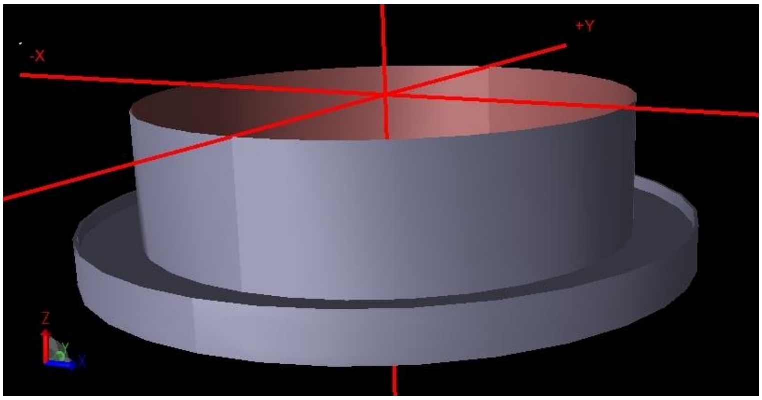


Figure 1: FPSO with proposed interceptor plate and heaveplate.

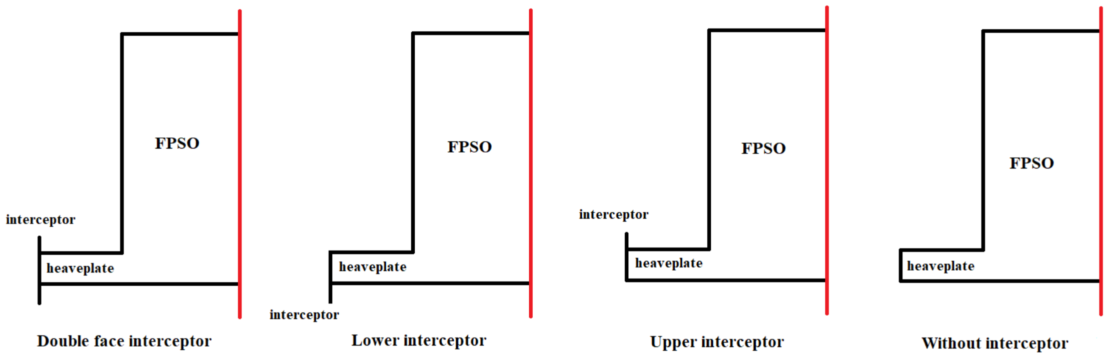


Figure 2: Proposed interceptor plate at different position arrangements.

3. Experiments

The present experimental tests were conducted at the University of Strathclyde's Kelvin Hydrodynamics Laboratory. The experimental test was aimed to examine the influence of adding an interceptor plate to the cylindrical FPSO concept.

3.1. Experimental facilities and instruments

The experiments were carried out using a scale model of a cylindrical FPSO unit modified by adding the proposed interceptor plate. Considering the tank dimensions and the wave reflection from the tank sides during the test, a geometrical similarity scale of 1:100 was selected for the model. The model was placed in the middle of the tank by using elastic mooring lines from four corners. The Kelvin tank has a length of 76 m, a width of 4.6 m and a water depth of 1.9 m.

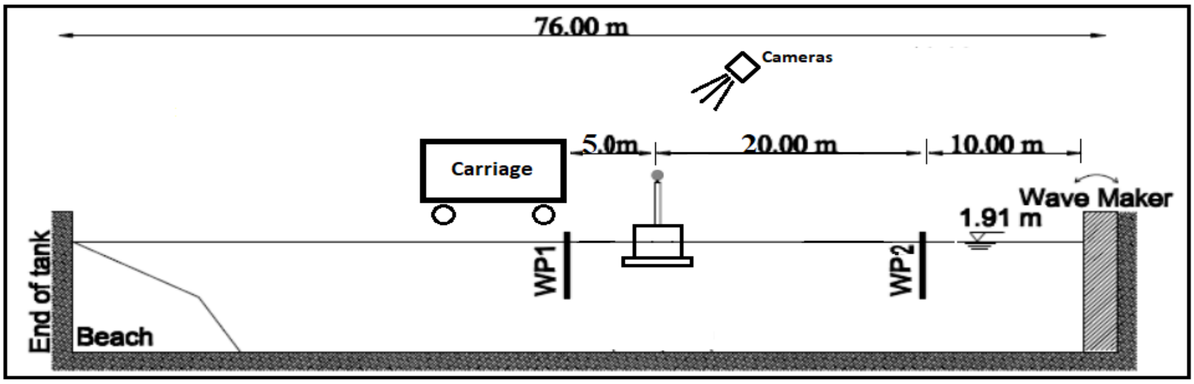


Figure 3: Schematic of Kelvin hydrodynamic tank.

The tank is equipped with a wave maker located at the end of the basin. The wave maker is capable to create regular and irregular waves according to input wave height and frequency. At the other side of the tank, the sloped absorption facilities are located in order to damp and reduce the reflected waves. The tank is provided with a carriage that has an electronic control system to operate and obtain the desired data. A monitoring system to capture the wave profile inside the tank using two probes located at 10 m from the wave maker and the ultrasonic wave probe is attached on the carriage as shown in Figure 3.

Figure 4: FPSO model moored inside the tank and Qualisys camera system tracing its motion.

Three 6-DOF QUALISYS motion cameras are located above the model, as illustrated in Figure 4. The cameras were employed to capture the motion of the FPSO model among waves. The model motion was detected with a body-fixed coordinate system, and motions were calculated and outputted in real time through Spike2 V9.06 data converter.

3.2. Model description

The cylindrical FPSO model has been introduced by Amin et al. [1-4]. Amin's model was modified in this study by adding an interceptor plate above the model heaveplate. The full-scale FPSO vessel has a diameter of 70 m and depth of 32 m. The vessel's main deck has a diameter of 87.5 m. The vessel's heaveplate, which is attached to the bottom of the vessel, has same diameter of 87.5 m and height of 2.5 m. The dimensions of the full scale and the model scale of the FPSO vessel are given in Table 1. The FPSO model was built from foam, wood and fiberglass. The interceptor plate was made of aluminium strip and fixed with screws. The model with interceptor plate is shown in Figure 5.

Table 1: FPSO full-scale and model scale dimensions.

Parameters	Full scale	Model (λ=1/100)	Scaling Factor
FPSO main deck diameter [m]	87.5	0.875	λ
FPSO central diameter [m]	70	0.7	λ
Heaveplate diameter [m]	87.5	0.875	λ
FPSO depth [m]	32	0.32	λ
Draft [m]	14.4	0.144	λ
Platform displacement [ton]	62680	0.06115	λ^3
VCG [m]	13.89	0.1389	λ

Wave frequency [Hz]	0.2 to 1	0.02 to 0.1	$\lambda^{-0.5}$

Figure 5: FPSO Model with interceptor plate.

3.3. Test matrix

The present test was divided into two groups. The first set was tested by using bare cylindrical FPSO hull without interceptor plate. While, the second set investigated the influence of additional different interceptor plate heights and arrangements on the motion behaviour of FPSO model. Different arrangements, namely upper interceptor plate, lower interceptor plate and double face interceptor plates, were tested at two different interceptor plate heights at 1m and 2 m, as illustrated in test matrix in Table 2.

Table 2: Test matrix.

No.	Test	Interceptor plate height [m]	Wave Frequency range [Hz]
1	FPSO without interceptor plate	-	0.02 to 0.1
2a	FPSO with Upper interceptor plate	1	
2b	FPSO with Upper interceptor plate	2	
3a	FPSO with Lower interceptor plate	1	
3b	FPSO with Lower interceptor plate	2	
4a	FPSO with double face interceptor plates	1	
4b	FPSO with double face interceptor plates	2	

4. Experimental motion behaviour

Since the motion responses have the largest impact on the operation and safety of offshore structures especially in harsh deployment areas, the vertical interceptor plate adding to FPSO hull is proposed in order to improve the heave and pitch motion. The influence of the proposed interceptor plate was investigated using experimental testing approach in frequency and time domains in a range of wave frequencies. The FPSO model with and without the proposed interceptor plate are shown in Figure 6.

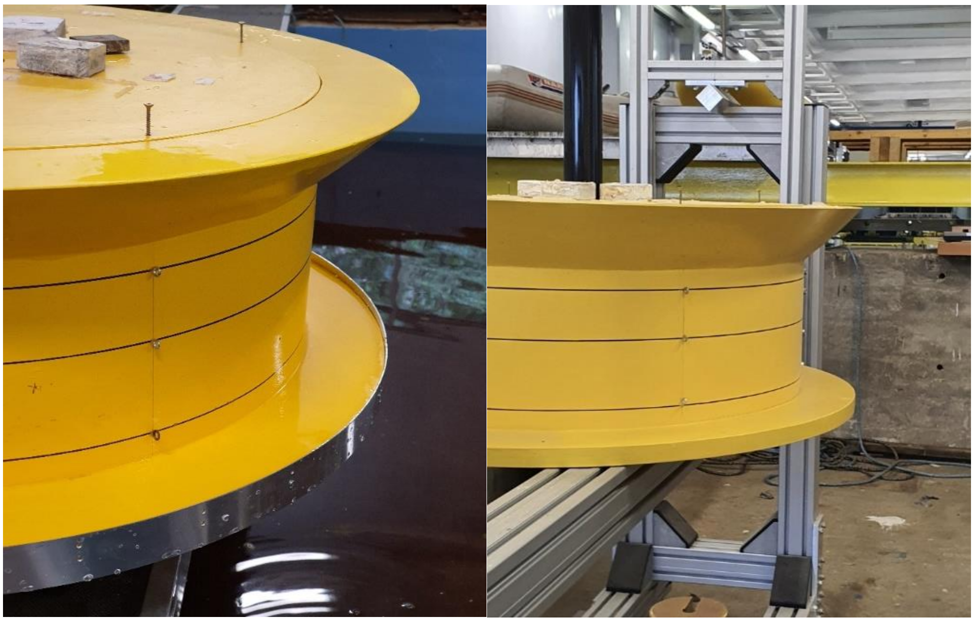
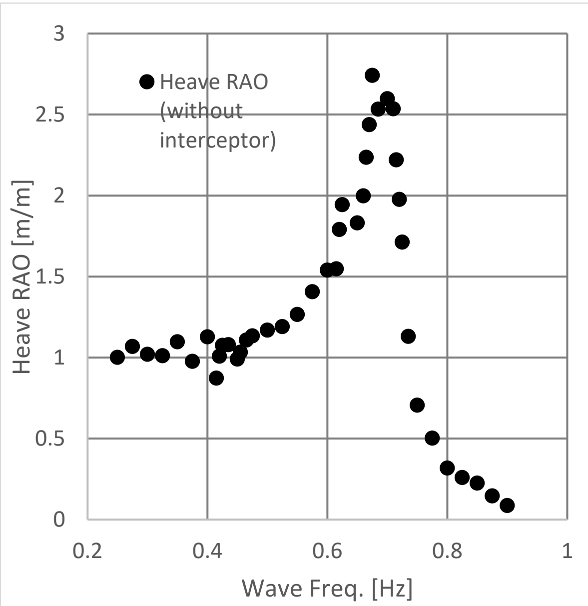
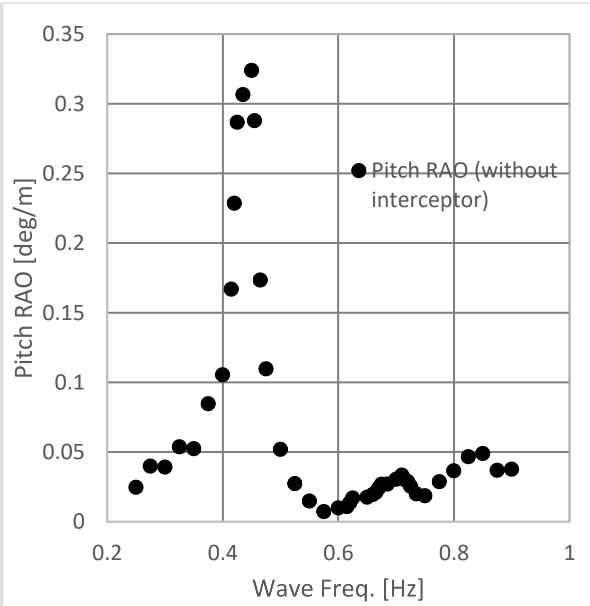


Figure 6: The FPSO model with and without the proposed interceptor plate.

4.1. Motion behaviour of FPSO without interceptor plate

The motion performance of the bare FPSO model without interceptor plate was tested and set as based case. The heave peak response can be observed near the heave natural frequency at 0.675 Hz, as shown in Figure 7(a). In the pitch response, the peak was observed at 0.45 Hz near the pitch natural frequency, as shown in Figure 7 (b).





a) Heave RAO

b) Pitch RAO

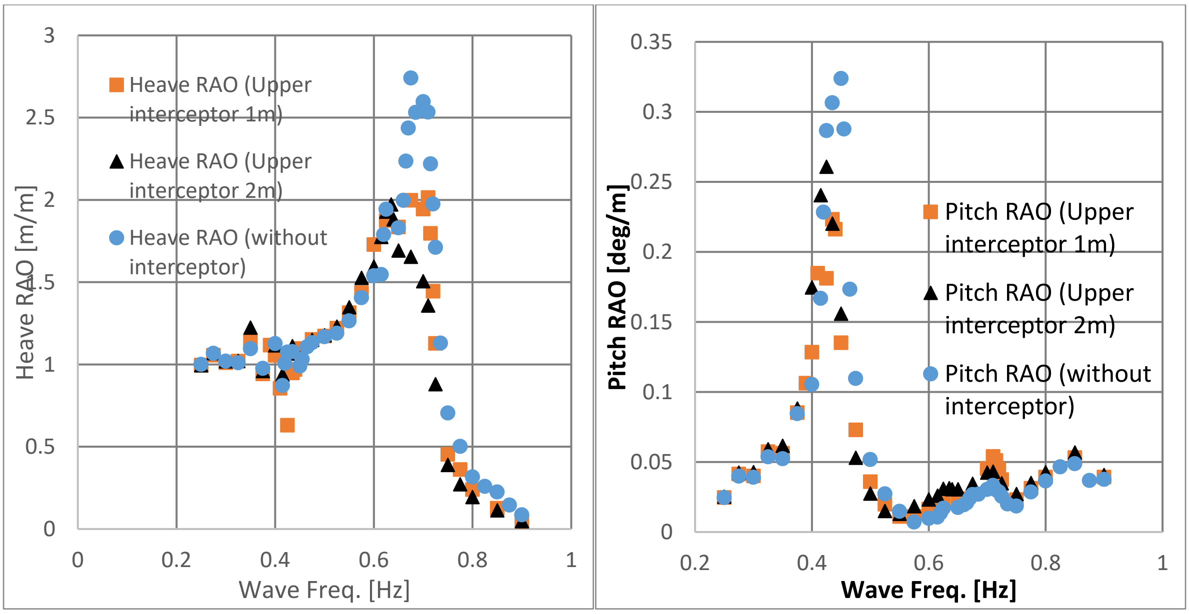
Figure 7: Heave and pitch motion behaviours for FPSO model at different wave frequencies.

4.2. Influence of the interceptor plate height on the motion behaviour of FPSO

For application on boats, many researchers have studied the optimum interceptor plate height to maximize the interceptor plate effectiveness in terms of improving hydrodynamic performance of planning vessels [8]. Due to interceptor plate drag force in high speed range, many researchers suggest to select interceptor plate height between 10 to 20 cm [9]. In this study, the interceptor plate is proposed to be used for FPSO vessels in order to improve the heave and pitch motion responses. Since the FPSO vessel is moored, the drag force is not a parameter to be concerned. Also, the unit size and displacement of FPSO are much larger than for boats. The influence of adding interceptor plate to the FPSO model on the motion responses are analysed in this section. Different interceptor plate arrangement and heights are tested at a range of wave frequencies. Two different heights 1 m and 2m were tested for different interceptor plate arrangements in the current study to illustrate the effect of interceptor plate height on the motion responses. The effect of a 1m and 2m interceptor plate height appears to be positive especially around FPSO natural frequency.

4.2.1. Upper interceptor plate

The FPSO model with upper interceptor plate is tested and the heave and pitch motion responses are plotted as RAO responses. Figure 8 shows the comparison between FPSO with interceptor plate and without for a range of wave frequencies. Reduction in heave response was observed by installing interceptor plate to FPSO model especially at model natural frequencies range for all interceptor plate heights. It can be noticed that reduction in heave responses is more remarkable around heave natural frequency and large wave frequencies rather than small frequencies. The same observation occurs in pitch response where the pitch motion's peak also decreases with respect to the bare FPSO model around pitch natural frequency. While, around pith secondary peak response (heave natural frequency), insignificant increase in response was observed.

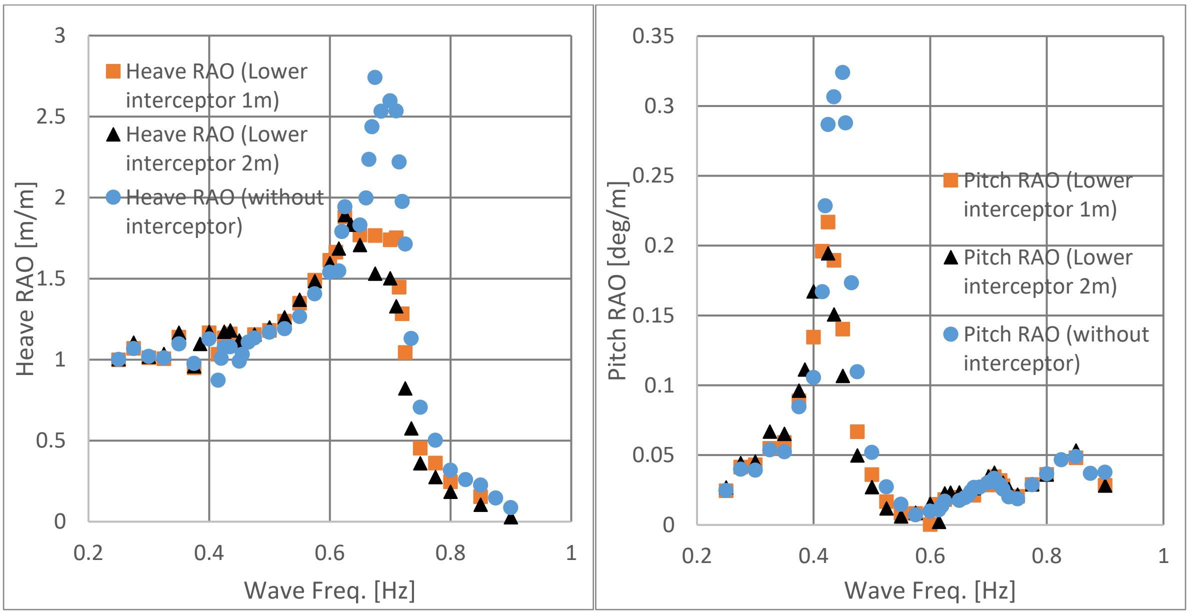


a) Heave RAO b) Pitch RAO

Figure 8: Heave and pitch motion behaviours for FPSO model with upper interceptor plate at different wave frequencies.

4.2.2. Lower interceptor plate

Lower interceptor plate is another arrangement which was tested in order to evaluate the influence of the interceptor plate position on the motion responses of the FPSO model. The RAO results are plotted in Figure 9 (a) and (b). The same observation occurs also for lower interceptor plate, where the heave and pitch responses decreased when the interceptor plate was fitted above the heaveplate. For heave response, the significant motion reduction was observed around the natural frequency and large wave frequency. At small wave frequency, no significant change in motion response was observed when the interceptor plate height increases. The same observation occurs for pitch response. The RAO responses decreased when the interceptor plate was added to the FPSO model.

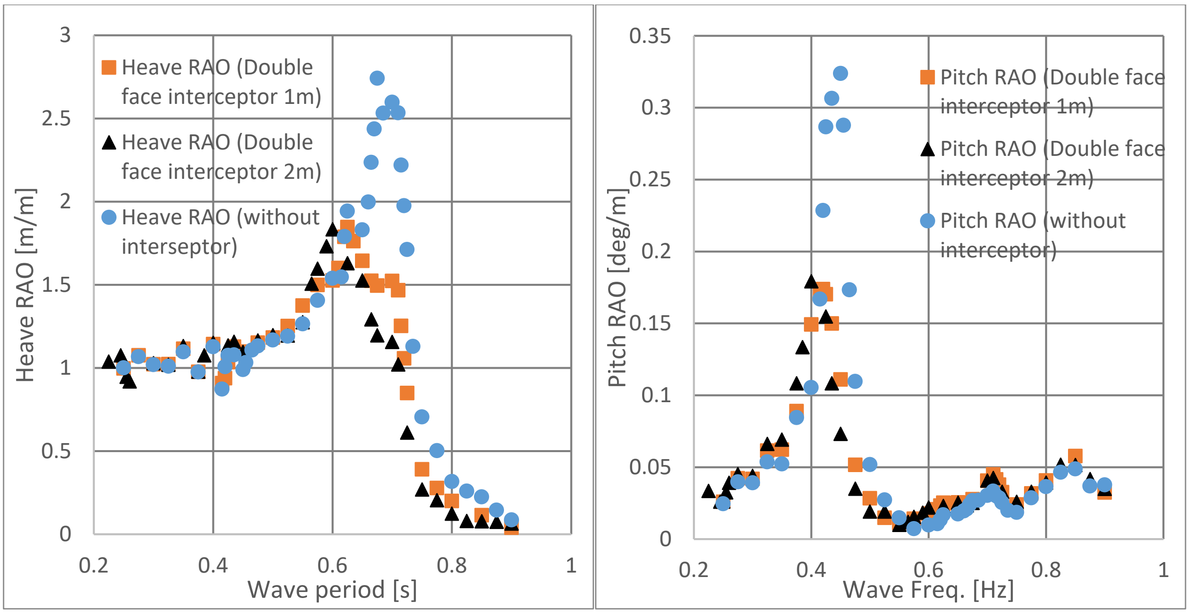


a) Heave RAO b) Pitch RAO

Figure 9: Heave and pitch motion behaviours for FPSO model with lower interceptor plate at different wave frequencies.

4.2.3. Double face interceptor plate

Double face interceptor plate was also tested and the results are plotted in Figure 10 (a) and (b). The same observation occurs also for the double face interceptor plate, where the heave and pitch responses decreased when the interceptor plate was fitted above the heaveplate. For heave response, significant motion reduction was observed around the natural frequency and large wave frequency. At small wave frequency, no significant change in motion response was observed for interceptor plate height increases. The same observation occurs for pitch response. The RAO responses decreased when the interceptor plate was added to the FPSO model.

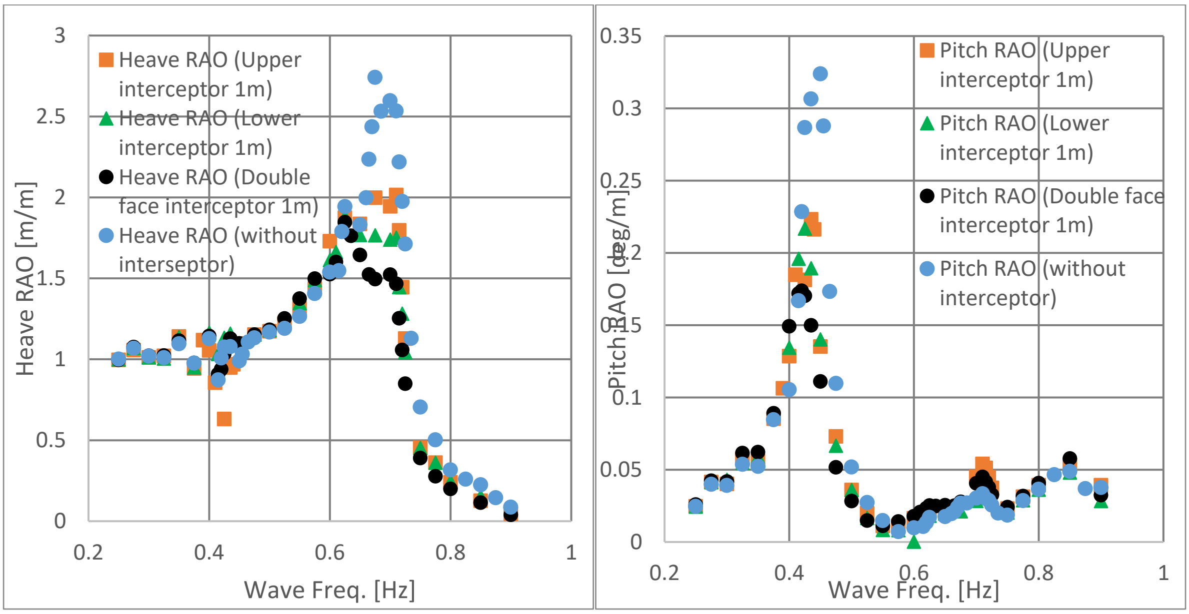


a) Heave RAO b) Pitch RAO

Figure 10: Heave and pitch motion behaviours for FPSO model with double face interceptor plates at different wave frequencies.

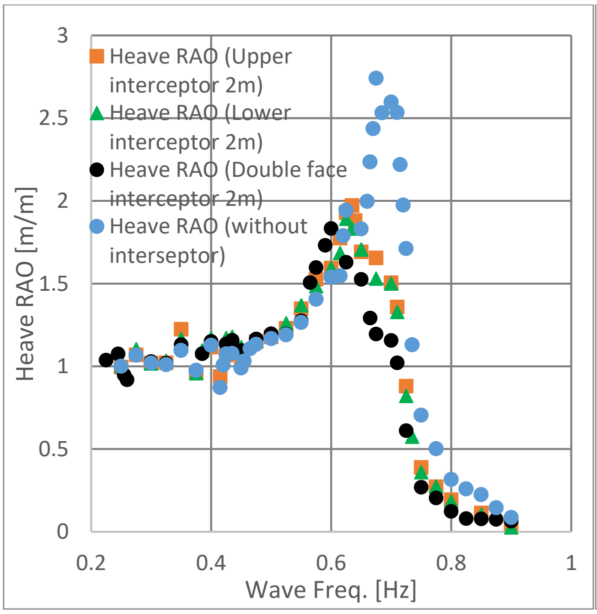
4.3. Influence of the interceptor plate position on the motion behaviour of FPSO

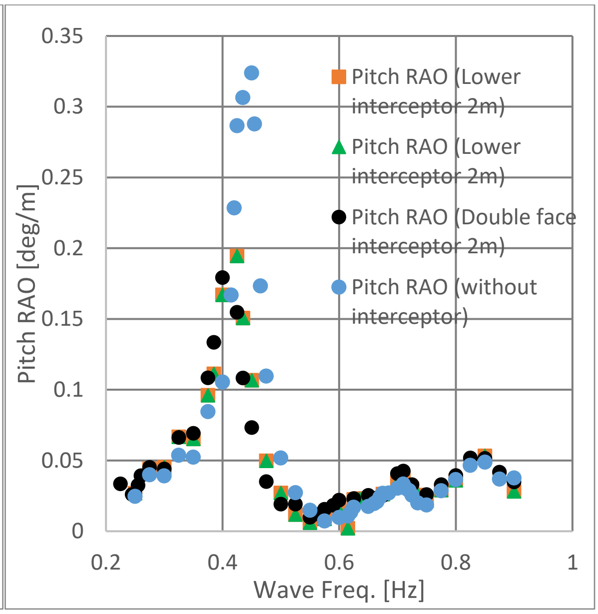
Different interceptor plate arrangements were tested in order to illustrate which arrangement can achieve the lowest motion responses. Figure 11 shows the heave and pitch responses of FPSO model without and with different interceptor plate arrangement at fixed interceptor plate height at 1 m and Figure 12 at fixed height 2 m. The comparisons for both interceptor plate heights show that double face interceptor plate is the best arrangement which shows the lowest responses for both heave and pitch motions.



a) Heave RAO b) Pitch RAO

Figure 11: Heave and pitch motion behaviours for FPSO model with different interceptor plate arrangement and fixed interceptor plate height at 1m.





a) Heave RAO

b) Pitch RAO

Figure 12: Heave and pitch motion behaviours for FPSO model with different interceptor plate arrangement and fixed interceptor plate height at 2m.

4.4. Heave and pitch motion improvement due to usage of the proposed interceptor plate

To evaluate the influence of interceptor plate on RAO responses of the FPSO model at heave and pitch natural frequencies, two comparison analysis are presented in Figures 13 and 14. The comparison results show that double face interceptor plate has the highest decrease in responses with respect to the FPSO response without interceptor plate. The RAO peak decrease in heave response for double face interceptor plates is up to 50% with respect to the FPSO model without interceptor plate. While in pitch response, decrease in response is 67% with respect to FPSO model without interceptor plate as shown in Table 3 and 4. It's importance to notice that there are changes in the peak strength and frequency due to installation of the interceptor plate. Therefore, the present comparison is absolute RAO peak without consideration to its frequency magnitude.

Table 3: Heave RAO peaks for different interceptor plate arrangements and interceptor plate heights.

Interceptor plate height [m]	Upper	Lower	Double face	Upper (reduction in response %)	Lower (reduction in response %)	Double (reduction in response %)
0	2.47	2.47	2.47	0	0	0
1	1.99	1.76	1.49	19.4	28.7	39.7
2	1.65	1.53	1.19	33.2	38.1	51.8

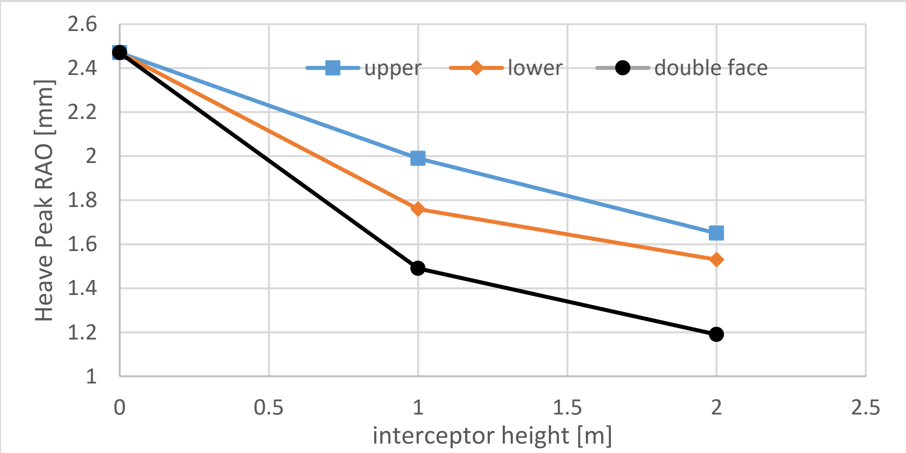


Figure 13: The relationship between heave RAO (at heave natural frequency) and interceptor plate height for different interceptor plate arrangements.

It can be noticed from the results in Figures 8,10 and 12 that the interceptor plate installation can reduce the fundamental heave and pitch natural frequencies of the model with more than 11% in case of 2m double face interceptor plates. In case of upper and lower interceptor plate arrangement, the reduction of heave and pitch natural frequencies could be between 5% to 7%.

Table 4: Pitch RAO first peaks for different interceptor plate arrangements and interceptor plate heights.

Interceptor plate height	Upper	Lower	Double face	Upper (reduction in response %)	Lower (reduction in response %)	Double (reduction in response %)
0	0.323	0.323	0.323	0	0	0
1	0.216	0.189	0.111	33.1	41.48607	65.6
2	0.194	0.19	0.106	39.9	41.17647	67.2

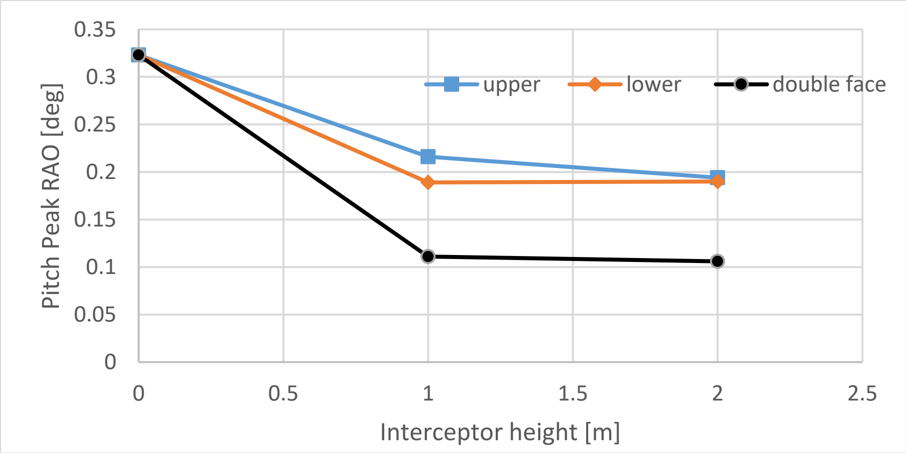


Figure 14: The relationship between pitch RAO (at pitch natural frequency) and interceptor plate height for different interceptor plate arrangements.

Quantification of the heave motion reductions due to usage of upper, lower and double interceptor plates are shown in Figures 15, 16 and 17. The reduction percentage was calculated with respect to the FPSO without interceptor plate. The results show that there is significant improvement in heave motion for wave frequencies above 0.6 Hz with up to 50% reduction in heave responses. While at wave frequencies lower than 0.6 Hz, insignificant negative effect was observed (average 5% increase in motion response).

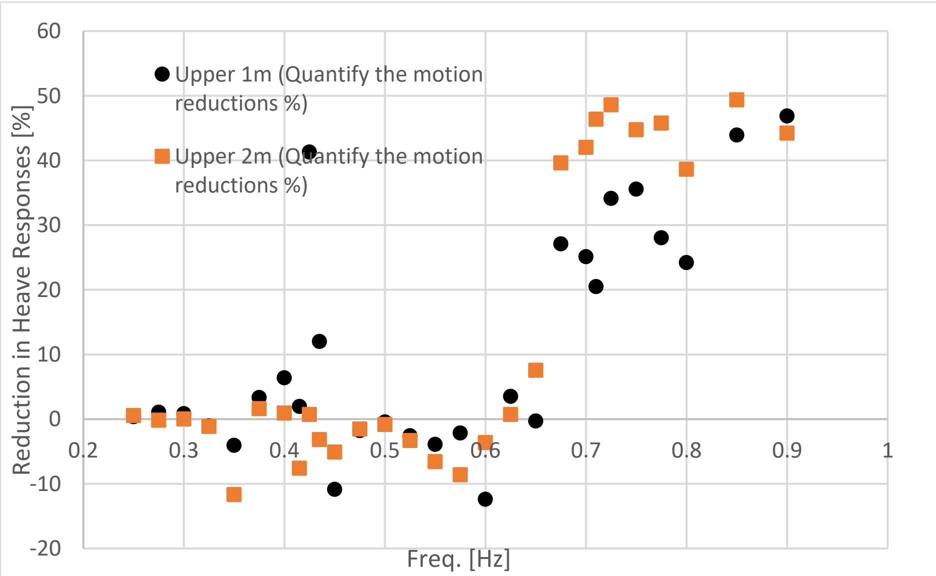


Figure 15: Reduction in heave responses due to usage of upper interceptor plate.

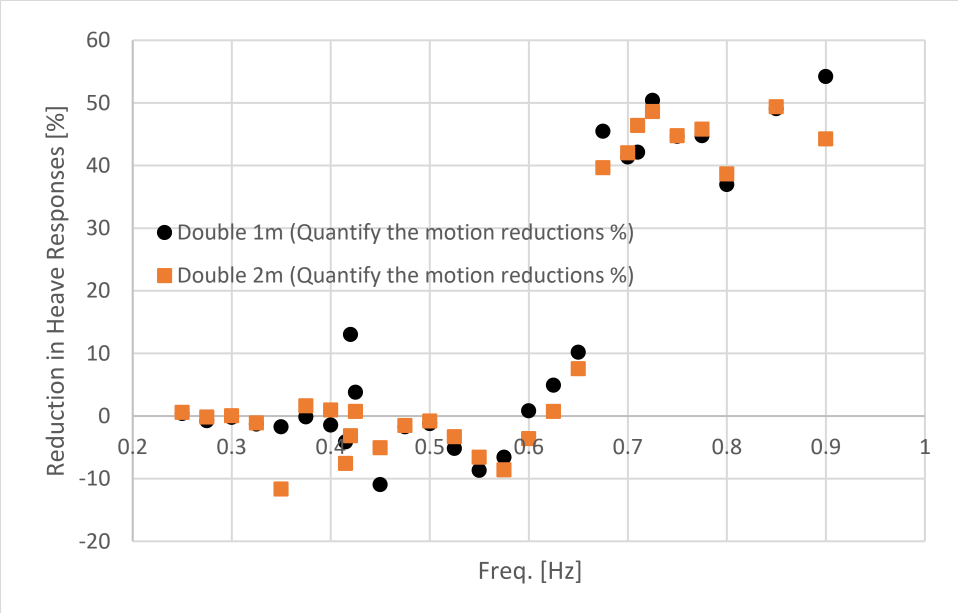


Figure 16: Reduction in heave responses due to usage of double interceptor plate.

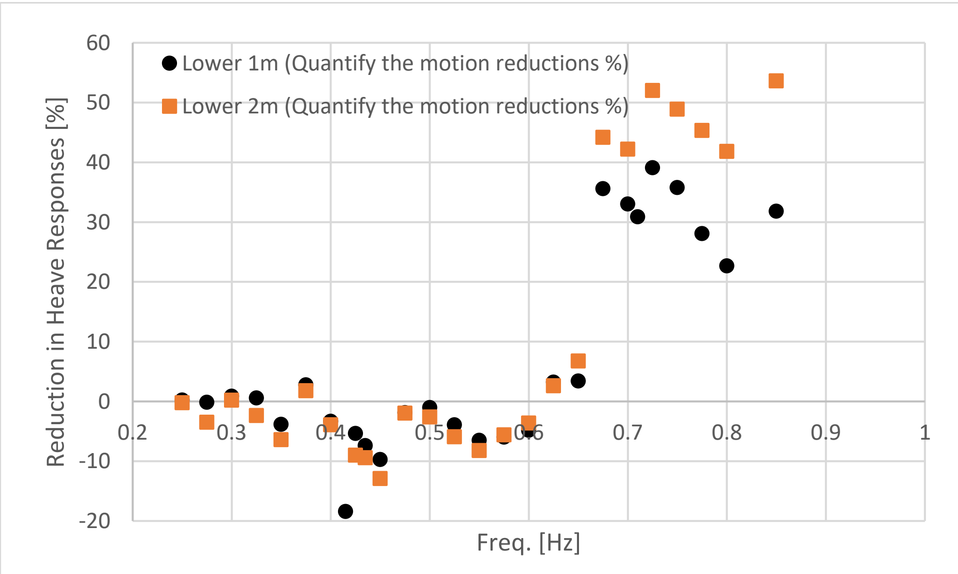
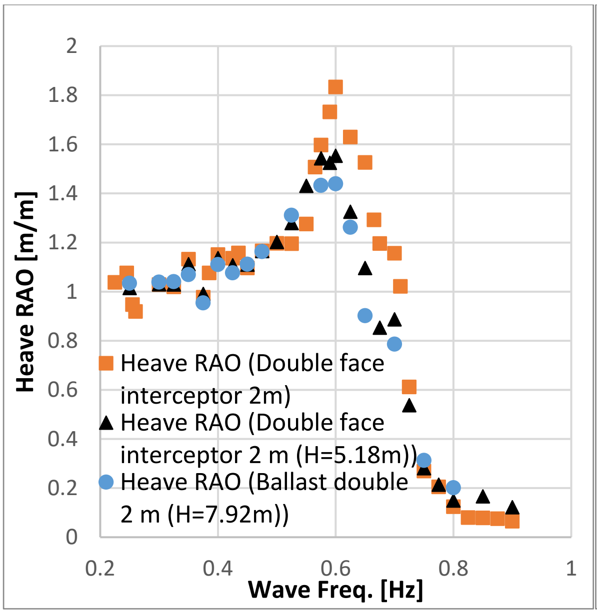
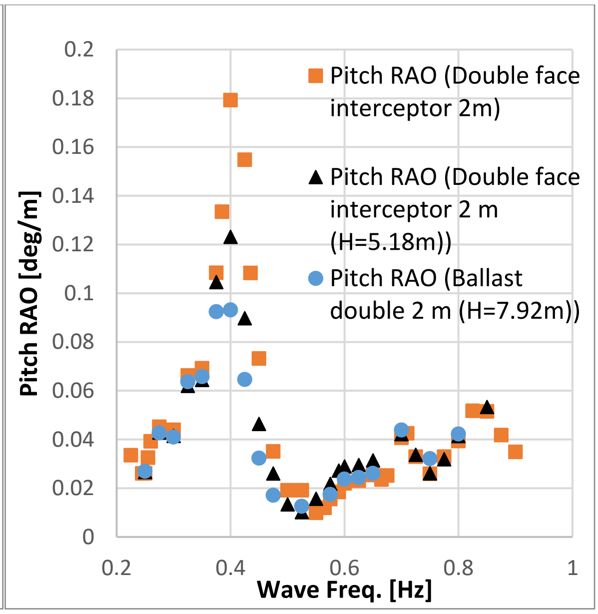


Figure 17: Reduction in heave responses due to usage of lower interceptor plate.

4.5. Effect of wave height

The relationship between the wave height and the RAO motion responses is demonstrated in this section. Three different wave heights were tested for a range of wave frequencies (2.15 m, 5.18 m and 7.92 m) as shown in the results in Figure 15. It was noticed that the effect of wave height on heave and pitch responses is very evident around natural frequencies as shown in Figure 18. However, for the remaining frequency ranges, the motion responses are not significantly different. It can also be observed that as the wave height amplitude increases, heave peaks decrease slightly. This is simply due to the fact that the viscous damping increases with the wave height.





a) Heave RAO b) Pitch RAO

Figure 18: Heave and pitch motion behaviours for FPSO model with 2 m double face interceptor plate at different wave heights.

4.6. Motion time history of FPSO model

The time series of the heave and pitch motion responses of the FPSO model with/without interceptor plate at model natural frequencies are analysed in this section. FPSO model heave response time series without and with different interceptor plate arrangements (1 m height) is shown in Figure 19. It is important to notice that the double interceptor plate arrangement has the lowest heave response with respect to without, upper and lower interceptor plate. The same observation occurs in pitch motion. The FPSO model with double interceptor plate arrangement has also the lowest response. In pitch response motion, unsymmetrical response is noticed for lower interceptor plate arrangement compared to other configurations. It is observed that the fluctuation pitch range decreases at lower part of the oscillation curve. More damping may occur when the model is pitched by aft rather than is pitched by fore as shown in Figure 20. The difference in time series behaviour can be related to the increase of pitch added mass due to installation of lower interceptor plate which can trap additional water.

Another interceptor plate height at 2 m was tested and the time series results are compared in Figures 21 and 22. The double face interceptor plate has the lowest heave and pitch responses with respect to other arrangements.

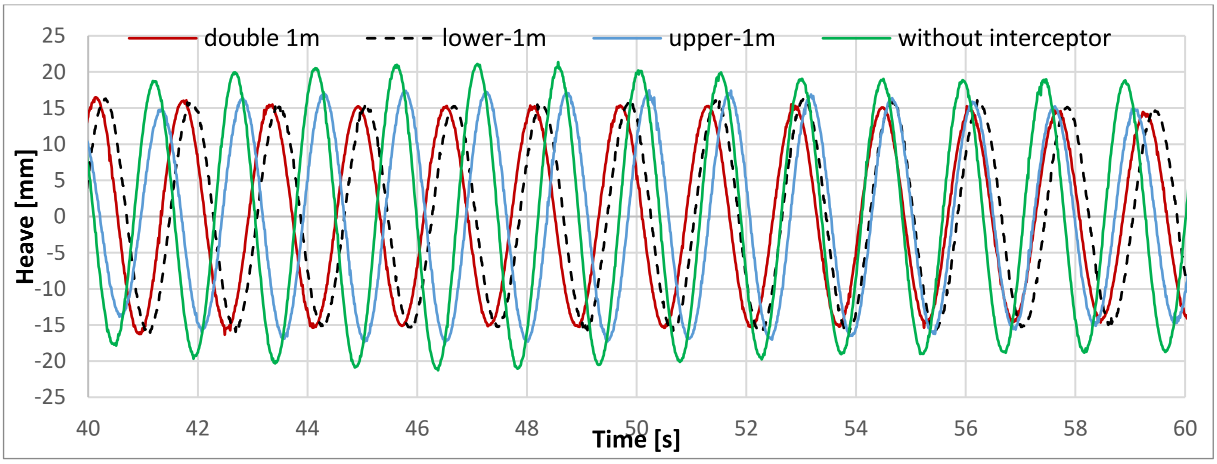


Figure 19: Heave time series history of FPSO model without and with 1 m interceptor plate height and different arrangements.

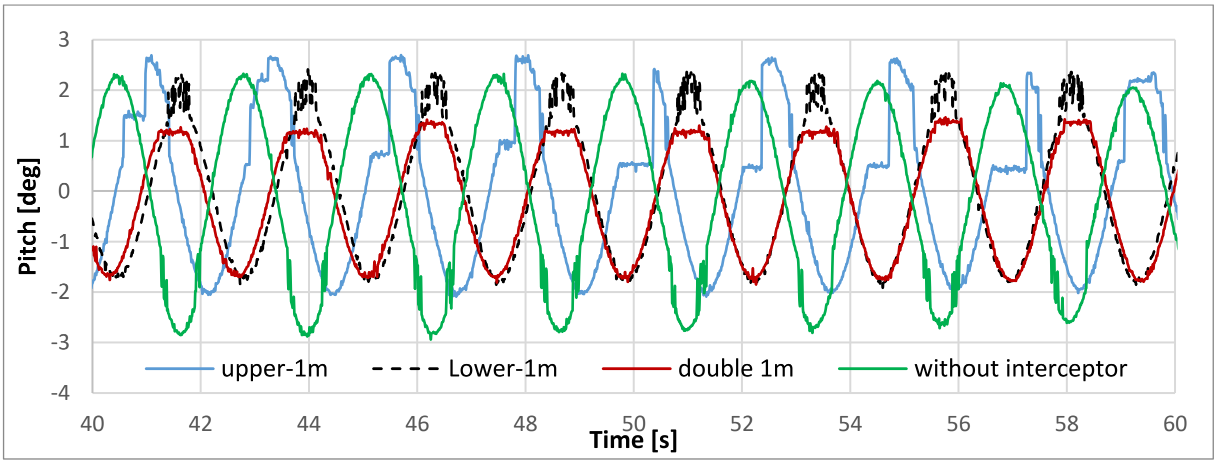


Figure 20: Pitch time series history of FPSO model without and with 1 m interceptor plate height and different arrangements.

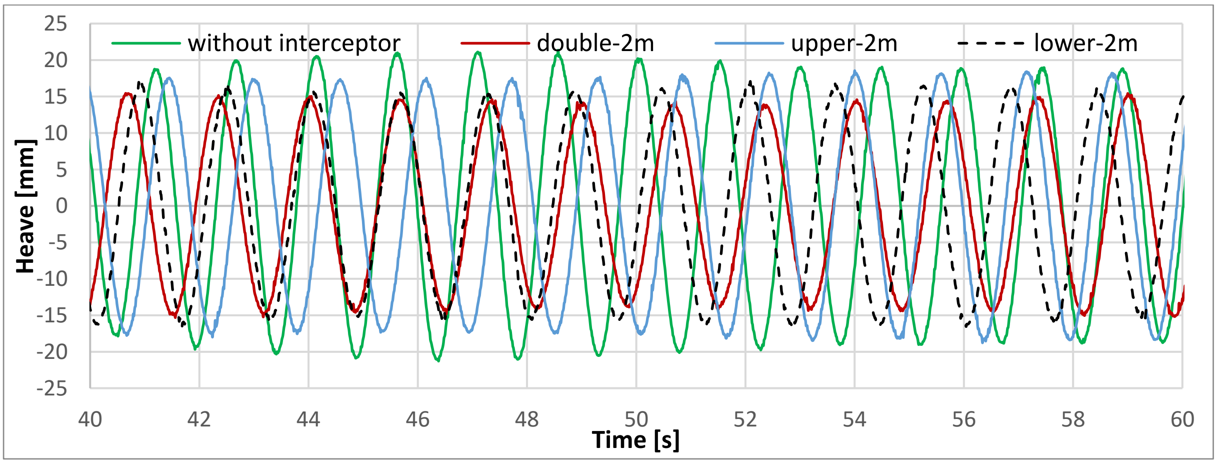


Figure 21: Heave time series history of FPSO model without and with 2 m interceptor plate height and different arrangements.

In order to illustrate the influence of interceptor plate height for double interceptor plate arrangement, two interceptor plate heights 1 m and 2m were tested and the time series are compared in Figure 20 and 21. It can be noticed that no significant change in heave and pitch time series are observed when the interceptor plate height increases from 1m to 2 m.

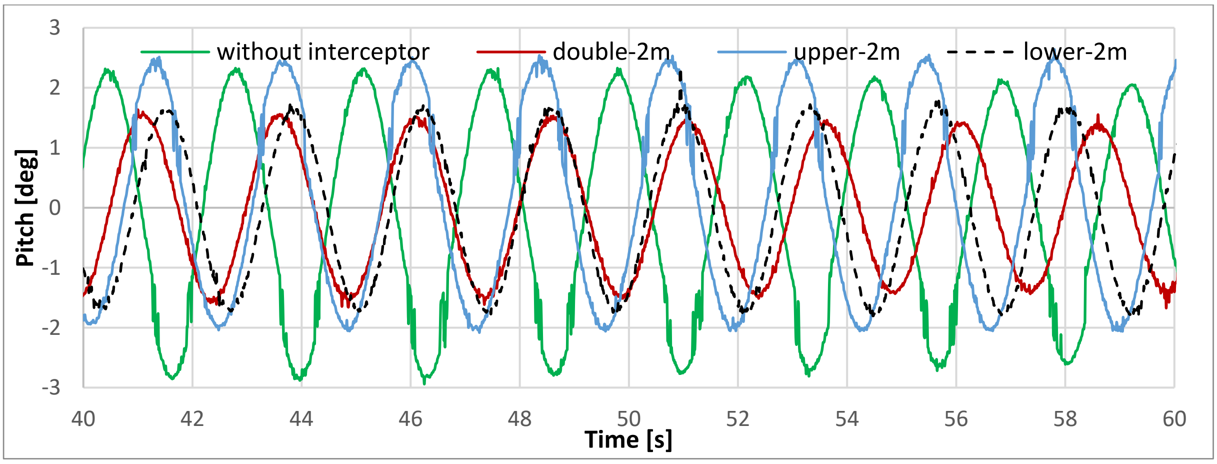


Figure 22: Pitch time series history of FPSO model without and with 2 m interceptor plate height and different arrangements.

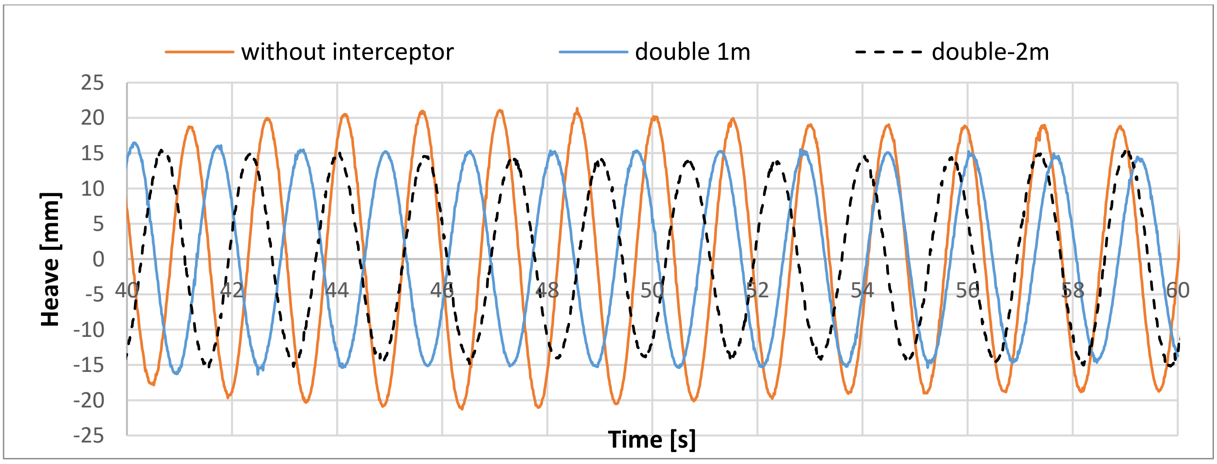


Figure 23: Heave time series history of FPSO model with double face interceptor plate for different interceptor plate heights.

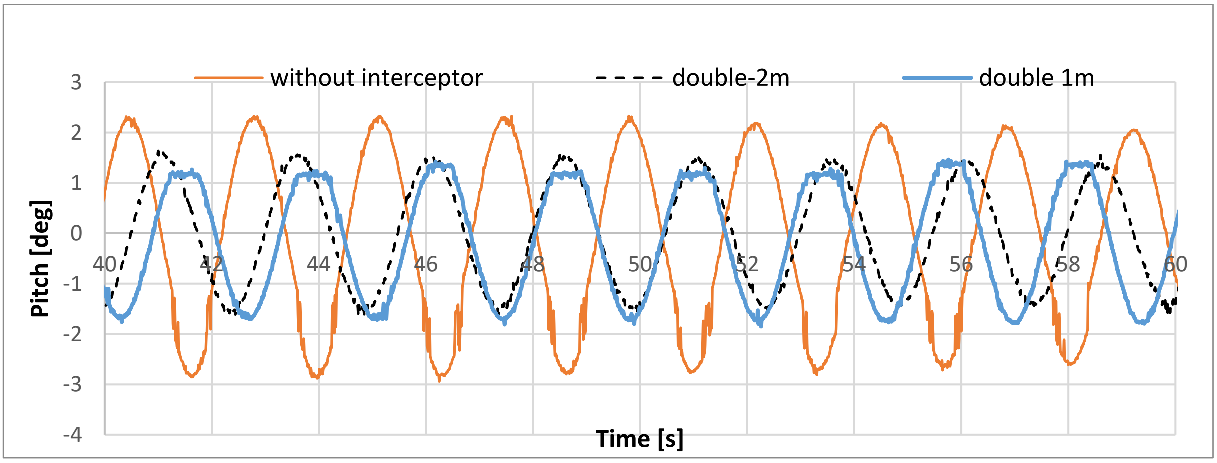


Figure 24: Pitch time series history of FPSO model with double face interceptor plate for different interceptor plate heights.

5. Conclusion

Controlling the motion responses of offshore structures can improve the dynamic performance and reduce the risk during the operation. Cylindrical FPSO design often experience significant heave and pitch motion responses especially when operation in harsh environmental conditions. Interceptor plate appendage was proposed in this study to reduce the motion responses. Evaluation of the motion performance of the FPSO model with and without the proposed interceptor plate was done by performing experimental tests for different interceptor plate heights and arrangements. A clear and significant benefit of installing interceptor plate is demonstrated near the heave and pitch natural frequencies. No significant change was observed in motion responses at small wave frequencies (lower than natural frequency range). A remarkable reduction in heave motion responses in large wave frequency near natural frequency range. Three interceptor plate arrangements (upper, lower and double face interceptor plates) were tested and the double face interceptor plate provide the highest motion reduction benefit. Based on the model result analysis, the peak responses of heave RAO decrease about 50% when adding 2 m height double face interceptor plates with respect to FPSO model without interceptor plate. While the peak responses of pitch RAO decrease about 67% for the same interceptor plate arrangement and height. Furthermore, the results show that there is significant improvement in heave motion for wave frequency above 0.6 Hz up to 50% reduction in heave responses.

The experimental results show that interceptor plate installation can reduce the fundamental heave natural frequency of the model with more than 11% in the case of 2m double face interceptor plates with respect to FPSO without interceptor plate case. The same observation occurs in the pitch natural frequency responses where the damped natural frequencies also decrease about 11%. Increase in the interceptor plate height from 1 m to 2 m yields slight improvement in the motion responses in heave motion with about 10%. While in pitch motion, the increase the interceptor plate height does not have significant benefit in pitch responses.

Finally, the present study was conducted in regular sea waves and further experimental investigation in irregular sea state is recommended for a future study.

Acknowledgments

The authors acknowledge the University of Strathclyde's Department of Naval Architecture, Ocean and Marine Engineering and Desert Research Centre for the technical expertise and support provided during the period of research. The authors would also like to acknowledge the Kelvin Hydrodynamic Laboratory technician team including Steven Black, Grant Dunning, Bill Wright, Rebecca McEwan for their technical support through the model construction and experiment setup.

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