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Hydrodynamics of external turret moored FPSO system

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The dynamic behavior of a 1:100 scale model of 140000 DWT turret moored FPSO system for three operating conditions, *i.e.*, 40 % DWT, 70 % DWT and 100 % DWT with three hawser lengths, *i.e.*, 15 %, 20 % and 25 % of the length of FPSO is discussed in this paper. The model tests were conducted in the 2 m wide wave flume under regular waves for the wave frequencies ranging from 0.55 Hz to 1.25 Hz in steps of 0.04 Hz at a water depth of 1 m for head sea condition. The motion response was measured using rotary type potentiometers. The mooring and hawser line forces were measured using specially fabricated ring type load cells. The test results of the forces and motion response were analyzed for the three hawser lengths at three operating conditions. From the analysis of the results, it is found that the tension in the forward mooring line is more than the tension in the aft mooring line for all loading conditions and hawser lengths. It is also observed that the tension of the forward mooring line decreases with increase in hawser length. The mooring tension is maximum for all hawser lengths at the full load condition.

[**Key words:** FPSO system, external turret, CALM, motions, mooring, hawser line tension, hydrodynamics]

Introduction

Of the large variety of mooring systems based on the single point mooring (SPM) principle[1], the turret concept is an attractive concept for floating production, storage and offloading (FPSO) of oil at offshore locations. The external turret type[2] is a special kind of single point mooring system composed of a relatively small turret structure suspended from a weather-vaning bearing incorporated in a rigid extension structure connected to the bow or stern of the vessel, and it is attached to the sea-bed by catenary anchor leg mooring (CALM)[2,3]. The turret includes bearings which constitute the interface between turret and vessel, allowing the vessel to rotate freely around its mooring legs in response to changes in environmental excitation and system dynamics. To maintain optimal conditions for floating production, storage and offloading vessel operations, it is essential to study the vessel motions, mooring forces and hawser line tension of the moored vessels due to wave induced loads. Hence, the present experimental work has been programmed on a typical turret moored FPSO model by CALM which has been subjected to regular sea waves to investigate its dynamic behaviour due to different hawser lengths and operating conditions.

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Materials and Methods

In a large number of ocean engineering problems, there are two types of important forces. When the ratio between these two types of forces is kept same for model and prototype, the model becomes dynamically similar to that of the prototype. In determining the mooring forces due to wave action, gravity and inertia forces govern and their relationship is derived from the Froude model law, wherein the Froude number must remain constant between model and prototype. For the present study 1:100 scale was chosen between model and prototype. The details of prototype and model are given in the Table 1.

Model

The modeling procedure of FPSO, turret system and mooring arrangement[4] is briefly described. FPSO

Table 1—Details of prototype and model FPSO particulars

Description	Prototype	Model Scale (1:100)
Deadweight (tones)	140000	0.140
Length (m)	270.7	2.707
Breadth (m)	44.3	0.443
Depth (m)	21.7	0.217
Fully loaded draught (m)	16.7	0.167
	Wave particulars	
Wave height (m)	5	0.05
Wave period (s)	8-18	0.8-1.8
Water depth (m)	100	1.0
	Turret mooring particulars	
Diameter of turret (m)	22.5	0.225
Type of Mooring	CALM	CALM
No of mooring lines	2	2
Material of mooring line	Steel stud link chain	Steel open link chain
Mooring line weight per unit length (N/m)	3532	0.003532

model was made in fiber reinforced plastic material with the transverse sections (Fig. 1) The block coefficient (C_B) of the model is 0.840. The length to breadth ratio is 6.11 and breadth to draft ratio is 2.65. The self-weight of the model is 37.30 kg. The model was ballasted with additional weights of 42.30 kg, 107.23 kg and 134.45 kg in order to achieve 40 %, 70 % and 100 % DWT respectively.

The external turret system was fabricated with PVC and Perspex materials. The weather-vaning bearing arrangement was provided at the top of the turret, and a hook was fixed on it in order to connect the hawser line of the FPSO model. The turret turn table clears the still water surface by 43 mm. Chain pipes were provided inside the turret body to connect the steel mooring chains.

Steel chain fitted with a load cell was used as the hawser line to connect FPSO and the turret body. The length of the hawser line was kept as 15 %, 20 % and 25 % of length of the FPSO model. The chain was selected similar to the mooring chain.

Mild steel angles were used to connect the mooring lines. The FWD and AFT mooring lines of the external turret system were connected to the holes drilled in the mild steel angle which were firmly fitted to the flume bed with wooden wedges. The orientation of the two mooring lines was such that they would make an angle of 180° to each other. The entire anchoring arrangement simulates a catenary anchor leg mooring (CALM) system as shown in Fig. 2.

Model tests were carried in a 85 m long, 2 m wide and 2.7 m deep wave flume for three different operating conditions with three hawser lengths under regular waves in head sea condition. The present experimental investigation on FPSO model has been carried out with the following objectives:

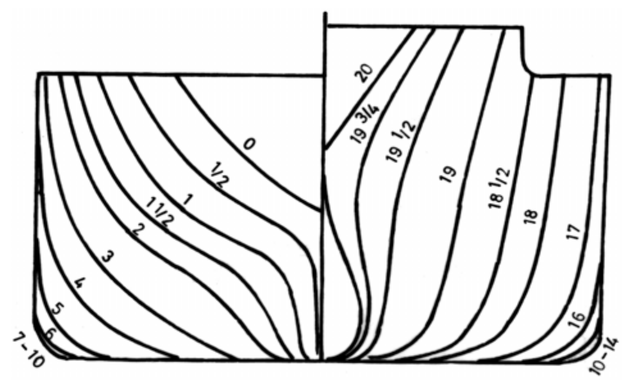

Fig. 1—Transverse sections of the FPSO model

(a) To determine the dynamic response of a FPSO model and mooring line forces for different operating conditions by keeping water depth as a constant under regular waves.
(b) To determine the hawser line tension for three hawser lengths and three operating conditions due to regular waves.
(c) To compare the dynamic performances, mooring line forces for different operating conditions, and different hawser lengths in regular sea waves.

For the present study, the turret moored FPSO model was kept at a distance of 40 m away from the flume wave maker, and one wave gauge was fixed at distance of 9 m from the model. The FPSO model was

Fig. 2—View of the external turret moored FPSO model

suitably ballasted to achieve the desired loading conditions, *i.e.*, 40 %, 70 % and 100 % DWT, respectively. Two mooring chains were connected with load cells to measure the mooring line tension. The hawser line was connected between the FPSO model and external turret system with a load cell to measure the hawser line tension. The water depth was kept as 1.0 m. The complete view of the external turret moored FPSO system and the experimental setup are shown in Figs.3 and 4 respectively.

The water surface elevation was measured by means of a wave gauge. The calibration constant of the wave probe is calculated as 1 volt = 18 mm/volt.The motion response in the surge, heave and pitch directions were measured with three rotary type potentiometers. The calibration constant of the three rotary potentiometers are calculated as 4.925, 4.929 and 4.937 cm / volt. The range of the potentiometer is ± 10 v. The forces of the mooring lines were measured using load cells. The turret moored FPSO model with its instrumentation was oriented along the center line of the flume with its bow facing the wave paddle to simulate the head sea condition as presented in Fig. 4.

The experiments were carried out for wave frequencies ranging from 0.55 Hz to 1.25 Hz in steps of 0.04 Hz for a wave height of 50 mm. Mooring lines

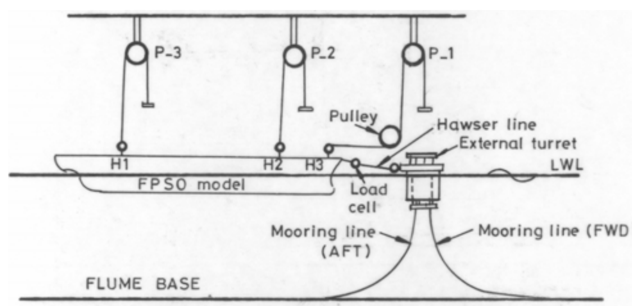

Fig. 3—Experimental set up

were given initial pretension of 2 N before starting the experiment. The incident wave height, forces in mooring lines, hawser line tensions and motion response of the model were obtained using the data acquisition system shown in Fig.4. The duration of each test was 2 minutes. The test procedure was repeated for three operating conditions *i.e.*,40 %, 70% and 100 % DWT with three hawser lengths *i.e.*, H_L/L_S = 0.15, 0.20 and 0.25.

Results and Discussion

(i) Mooring and hawser line forces

The measured tension in the mooring and hawser lines is normalized with the breaking strength of the mooring chain. The normalized line tension is plotted

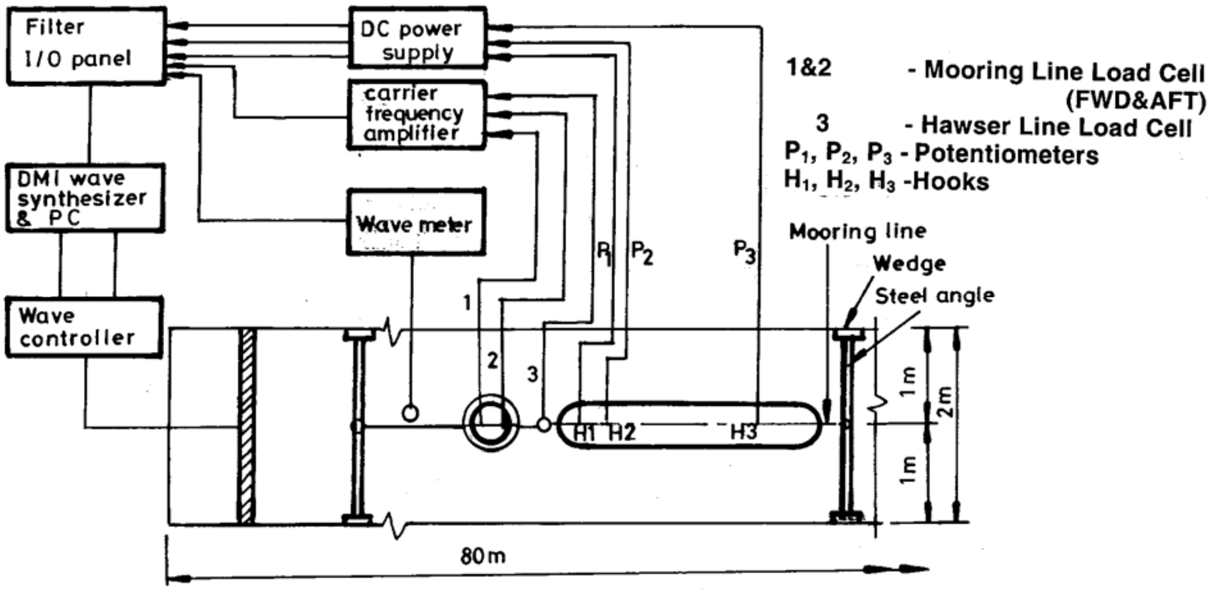

Fig. 4—Instrumentation of the model

Table 2—Normalized mooring and hawser line forces for different operating conditions with different hawser lengths at ω_L = 3.2

Description	H_L/L_S = 0.15			H_L/L_S = 0.20			H_L/L_S = 0.25		
	40% DWT	70% DWT	100% DWT	40% DWT	70% DWT	100% DWT	40% DWT	70% DWT	100% DWT
Mooring Line (Fwd)	0.1382	0.1560	0.1628	0.1249	0.1480	0.1505	0.1117	0.1384	0.1409
Mooring Line (Aft)	0.0378	0.0481	0.0521	0.0344	0.0174	0.0495	0.0314	0.0386	0.0421
Hawser Line	0.0315	0.0393	0.0463	0.0151	0.0174	0.0227	0.0098	0.0103	0.0107

against the non-dimensionalised wave frequency parameter, i.e., $\omega_L = \omega^2 L/2g$, where L is the length of the model, ω is the incident wave circular frequency in rad / sec, and g is the acceleration of to gravity. The variation of normalized mooring and hawser line forces at three operating conditions for three hawser lengths is presented in Table 2. The typical normalized mooring and hawser line tension are shown Fig. 5.

Fwd mooring line (H_L / L_S =0.15)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 16 % and 5 % less than that of 100%DWT respectively.

Fwd mooring line (H_L / L_S =0.20)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 18 % and 2 % less than that of 100%DWT respectively as shown in Fig.5B.

Fwd mooring line (H_L / L_S =0.25)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 21 % and 2 % less than that of 100 % DWT respectively.

Aft mooring line (H_L / L_S =0.15)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 28 % and 8 % less than that of 100 % DWT respectively.

Aft mooring line (H_L / L_S =0.20)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 31 % and 65 % less

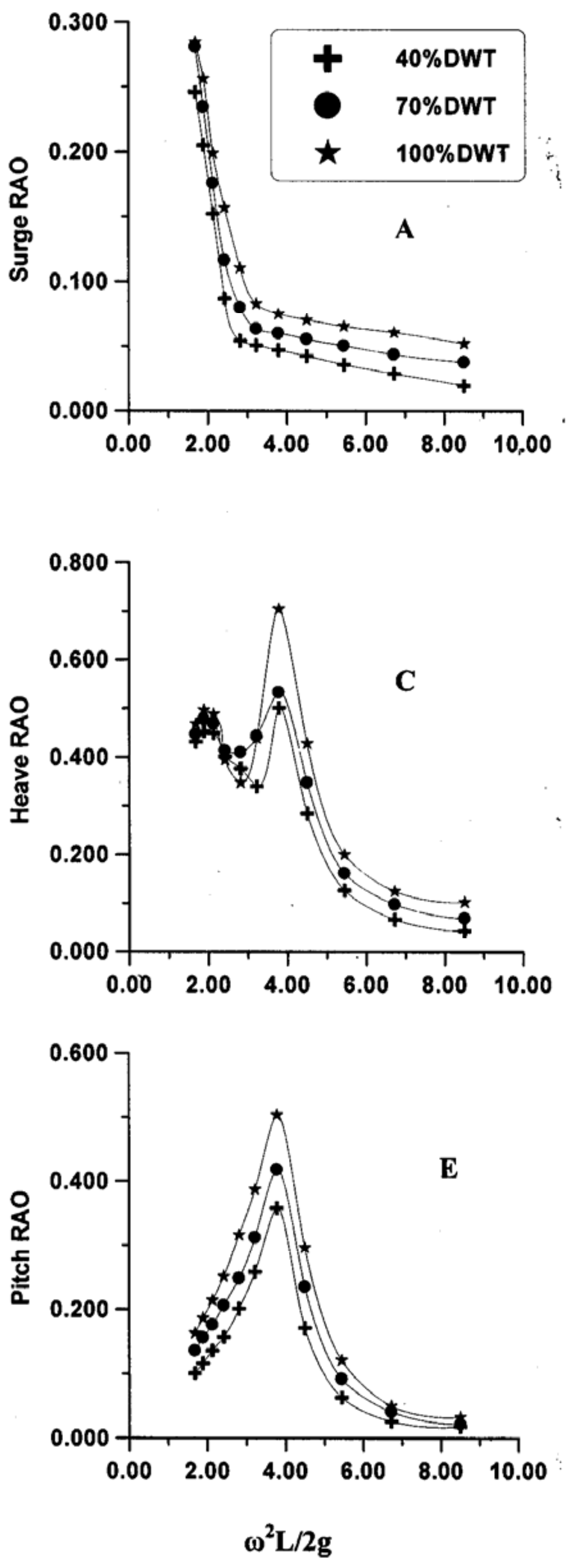

Fig. 5—Normalised motions and mooring and hawser line tensions Vs non-dimensionalized wave frequency parameter of external turret moored FPSO model moored by CALM arrangement at three loading conditions for $H_L/L_S = 0.20$.

than that of 100 % DWT respectively as shown in Fig. 5D.

Aft mooring line (H_L / L_S =0.25)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 40 % DWT at the same wave frequency, i.e., ω_L = 3.2, they are 26 % and 9 % less than that of 100 % DWT respectively.

Hawser line (H_L / L_S =0.15)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L =3.2, they are 32 % and 16 % less than 100 % DWT respectively.

Hawser line (H_L / L_S =0.20)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 34 % and 24 % less than 100%DWT respectively as shown in Fig.5F.

Hawser line (H_L / L_S =0.25)

By comparing the line tension of 40 % DWT and 70 % DWT with the maximum line tension corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.2, they are 9 % and 4 % less than 100 % DWT respectively.

At the natural frequency of the FPSO system, maximum tension in the forward and aft mooring lines is found to be at 100%DWT for all hawser lengths, varying from 31% to 38 % and 24 % to 42 %, respectively, with the increase in hawser length, whereas the maximum hawser line tension is observed at 40 % DWT for all hawser lengths varying from 10 % to 48 % with increase in hawser length.

(ii) Motion response

The motion response is usually represented as the Response Amplitude Operator (RAO), which is the ratio of motion amplitude to the wave amplitude or wave slope as detailed below:

Surge RAO = Response amplitude / Wave amplitude
Heave RAO = Response amplitude / Wave amplitude
Pitch RAO = Response amplitude / (Wave number × wave amplitude)

The variation of the motion response with the wave frequency parameter at three operating conditions for three hawser lengths is shown in Table 3. The typical normalized motions are shown in Fig. 5.

From the model test, the maximum surge, heave and pitch RAO are observed corresponding to 100 % DWT.

Surge RAO (H_L / L_S =0.15)

The maximum surge RAO corresponding to 40 % DWT is observed as 0.2629 at ω_L =1.679, and it shows a decreasing trend with increase in wave frequency. By comparing the surge RAO of 40 % DWT and 70 % DWT with the maximum surge RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 1.679, they are 17% and 8% less than that of 100 % DWT surge RAO respectively.

Surge RAO (H_L / L_S =0.20)

By comparing the surge RAO of 40 % DWT and 70 % DWT with the maximum surge RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 1.679, they are 13 % and 2 % less than that of 100 % DWT surge RAO respectively as shown in Fig. 5A.

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Surge RAO (H_L / L_S =0.25)

By comparing the surge RAO of 40 % DWT and 70 % DWT with the maximum surge RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 1.679, they are 10 % and 5 % less than that of 100 % DWT surge RAO respectively.

Table 3—Normalized dynamic response for different operating conditions with different hawser lengths

Description	H_L/L_S = 0.15			H_L/L_S = 0.20			H_L/L_S = 0.25		
	40% DWT	70% DWT	100% DWT	40% DWT	70% DWT	100% DWT	40% DWT	70% DWT	100% DWT
Surge ω_L = 1.679	0.2629	0.2901	0.3151	0.2460	0.2809	0.2843	0.1630	0.1720	0.1809
Heave ω_L = 3.779	0.5377	0.6287	0.8471	0.5011	0.5331	0.7048	0.4017	0.4272	0.4632
Pitch ω_L = 3.779	0.3840	0.4470	0.6050	0.3580	0.4180	0.5030	0.2890	0.3070	0.3300

Heave RAO (H_L / L_S =0.15)

By comparing the heave RAO of 40 % DWT and 70 % DWT with the maximum heave RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.779, they are 37 % and 26 % less than that of 100 % DWT heave RAO respectively.

Heave RAO (H_L / L_S =0.20)

By comparing the heave RAO of 40 % DWT and 70 % DWT with the maximum heave RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.779, they are 29 % and 24 % less than that of 100 % DWT heave RAO respectively as shown in Fig. 5C.

Heave RAO (H_L / L_S =0.25)

By comparing the heave RAO of 40 % DWT and 70 % DWT with the maximum surge RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.779, they are 14 % and 8 % less than that of 100 % DWT heave RAO respectively.

Pitch RAO (H_L / L_S =0.15)

By comparing the pitch RAO of 40 % DWT and 70 % DWT with the maximum pitch RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.779, they are 37 % and 26% less than that of 100 % DWT pitch RAO respectively.

Pitch RAO (H_L / L_S =0.20)

By comparing the pitch RAO of 40 % DWT and 70 % DWT with the maximum pitch RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.779, they are 29 % and 17 % less than that of 100 % DWT pitch RAO respectively as shown in Fig.5E.

Pitch RAO (H_L / L_S =0.25)

By comparing the pitch RAO of 40 % DWT and 70 % DWT with the maximum pitch RAO corresponding to 100 % DWT at the same wave frequency, *i.e.*, ω_L = 3.779, they are 12 % and 7 % less than that of 100 % DWT pitch RAO respectively.

The surge RAO follows the same trend, and it showed decreasing trend with increase in wave frequency and also with increase in hawser length for all operating conditions. The maximum response was observed at 100 % DWT for all hawser lengths varying from 10 % to 40 % with increase in hawser length.

The heave RAO showed increasing trend with increase in wave frequency upto the natural frequency of the FPSO system where the heave RAO is maximum , and thereafter the heave response showed the decrease in trend with the increase of wave frequency. The heave RAO also increased with increase in hawser length for all operating conditions. The maximum response was observed at 100 % DWT for all hawser lengths varying from 17 % to 45 % with increase in hawser length.

The normalized pitch response followed the increasing trend with increase in wave frequency similar to heave response, and a maximum pitch response occurred at the natural frequency of the FPSO system. Thereafter, pitch response decreased with increase of wave frequency .The pitch RAO also increased with increase in hawser length for all operating conditions and the maximum response was observed at 100 % DWT for all hawser lengths varying from 17 % to 45 % with increase in hawser length.

The observations obtained from the present experimental study also indicate that there exist always low frequency motions as well as slowly oscillating mooring forces which are inherent features of any moored floating structure. This inference is well in agreement with that of previous reports[5,6].

By comparing the motions of the FPSO model at fully loaded condition for different mooring configurations, i.e., VALM and CALM arrangements, it is noticed that the surge, heave and pitch motions of the FPSO model moored by CALM arrangement were 27 %, 25 % and 25 % less than that of VALM arrangement. Similarly, the normalized forward and aft mooring line tension of CALM arrangement were 44% and 54 % less that of VALM arrangement. In the case of hawser line, the tension is reduced by 50 % for CALM arrangement as compared to that of VALM arrangement.

Conclusion

- The mooring forces are not equally shared by both the forward and aft mooring lines. In all the operating conditions, the tension in the forward mooring line is more than the tension in the aft mooring line for all loading conditions and three hawser lengths.
- It is also observed that the tension of the forward mooring line decreases with increase in hawser length. The mooring tension is

maximum for all hawser lengths at the operating condition of 100 % DWT.

- The hawser line force is found to be minimum for 40 % DWT with H_L/L_S = 0.25 as compared to other operating conditions with different hawser length.
- In case of motion response, the surge RAO for 100 % DWT is comparatively low for longer hawser line in comparison with other conditions for all H_L/L_S ratios.
- The heave and pitch response of the FPSO follow the same trend for all operating conditions with the increase in hawser lengths.

The interaction between the turret structure and FPSO system is the main reason for the above variations in the dynamics of the turret moored system. Finally, it is suggested that the mooring system is to be designed to satisfy the operating condition of 100% DWT with H_L/L_S = 0.15 at which the forward mooring line is subjected to maximum mooring force so that the system will be safe for all other operating conditions.

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