EFFECT OF TURRET LOCATION ON THE DYNAMIC BEHAVIOUR OF AN INTERNAL TURRET MOORED FPSO SYSTEM

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Abstract

An experimental investigation on the motions and mooring forces of a typical internal turret moored Floating Production Storage and Offloading (FPSO) system under regular sea waves for different loading conditions i.e., 40%DWT, 70%DWT and 100%DWT with different turret locations viz forward, midships and semi- aft positions is reported in this paper. A 1:100 scale model of 140000 DWT turret moored FPSO system was tested in a 2m wide wave flume at a water depth of 1m for the wave frequencies from 0.55Hz to 1.25Hz in steps of 0.04Hz. The motions were measured by rotary type potentiometers and proving ring type load cells were used to measure the mooring forces. From the analysis of the experimental results, it is found that among the three turret locations, the forward turret position is the best suited position for the internal turret moored FPSO system, so as to have favourable and safe working environment. In this turret location, the surge, heave and pitch motions are about 20% to 30% less in comparison with mid ship and semi-aft positions for all loading conditions.

Keywords: FPSO system**,** internal turret, CALM, motions, mooring forces

1. Introduction

In the recent years, considerable research is being carried out on turret moored floating production, storage and offloading (FPSO) system operating at offshore locations. An internal turret moored FPSO system is an attractive concept for both production facilities and offshore storage. In an internal turret moored FPSO system, the turret structure is built inside the tanker's hull and it is attached to the sea-bed by catenary anchor leg mooring (CALM).The spider part of the turret located at the vessel keel level includes bearings, allowing the vessel to rotate freely around its mooring legs in response to changes in environmental excitation and system dynamics. In the case of internal turret moored FPSO system, the vessel motions and mooring forces are mainly governed by the location of the turret so as to maintain optimal operating conditions. Antonio Fernandes et al (1998) have investigated the use of stabilizers in FPSO's (Floating Production, Storage and Offloading) systems with a turret under the light of a reviewed perhaps new Stability Analysis specifically for the turret and an order of magnitude Analytical Approach. This has been made together with Model Testing results and Time-Domain Non-Linear simulations.De Boom (1987) has presented four different turret concepts covering a wide range of requirements. A more detailed outline follows, describing the two turrets designed and installed by SBM Inc., the Rospo Mare external stern turret system and the Jabiru disconnectable riser turret mooring.Delepine et al (1993) have discussed the factors that operators considering FPSO developments in harsh environments should evaluate when selecting between a permanent or disconnectable Single Point Mooring System. Donoghue.O' et al (1992) have carried out an experimental study of turret-moored floating production systems and presented model test results for motions and mooring line tensions for a range of long-crested and short-crested seas in order to identify general motion characteristics of turret-moored systems. They have also highlighted important role played by turret position and wave spreading. Garza-Rios et al (1996) have developed a design methodology to reveal the dependence of nonlinear slow motion dynamics of Turret Mooring Systems (TMS) on several design parameters, such as water depth, turret location and mooring line pretension. For a given TMS configuration, catastrophe sets are developed in the parametric design space, showing the dependence of

stability boundaries and singularities of bifurcations on design variables. This methodology eliminates the need for extensive nonlinear simulations.

Huang et al (1993) have presented model test and analytical correlation results of a single point moored Floating Production, Storage and Offloading tanker based system. Both Permanent and Disconnectable turret mooring system are considered. Analytical calculation of green water effects, vessel motions, turret motions, turret and mooring line loads are compared with model test results.   Frequency and time domain analysis techniques of calculating line tensions are demonstrated and results are compared to the model tests measured time histories. Lentz et al (1991) have focused on defining key system components, including the sub sea systems, and the combination mooring/thruster station keeping system, for one set of field parameters, and culminated in the development of a conceptual design of a turret-moored production system (TUMOPS).Liu et al (1998) have described physical model testing of a moored monohul with varying turret location conducted in the Ocean Wave Basin at HR Wallingford. The vessel and moorings are examined in weather conditions such that wind induced loading causes the vessel to take up a non-zero mean yaw offset to the waves. The experimental results are compared with time domain simulation of non-linear drift motions. Conclusions are drawn upon the influence of turret position on the motions of the moored vessel in non-head-sea situations. Results for varying wind direction relative to waves are also presented. Based on the review of these existing literatures, it is found that no information is available for the comparison of the dynamic behaviour of the internal turret moored FPSO system at different loading conditions with various turret locations under the action of waves. Hence, the present experimental investigation has been programmed for a typical internal turret moored FPSO system by catenary anchor leg mooring (CALM) which has been subjected to regular sea waves, in order to get insight knowledge on its dynamic behaviour due to three turret locations with different loading conditions.

Table 1: Details of Prototype and Model

FPSO PARTICULARS		
DESCRIPTION	**PROTOTYPE**	**MODEL** **Scale (1:100)**
Dead weight (tonnes)	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
Weight of mooring line (N/M)	3532	0.3532
Breaking strength of mooring line (kN)	7800	0.0078

2. Prototype and Model

In a large number of ocean engineering problems, the number of important types of forces are two, so that when the ratio between the two types of forces is kept same for model and prototype, the model becomes dynamically similar to that of the prototype. In modelling, most forces are governed by gravity and inertia forces.   In such cases, the model scale may be derived from the Froude model law. Then the ratio between gravity and inertia is also the same. 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 the same 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.
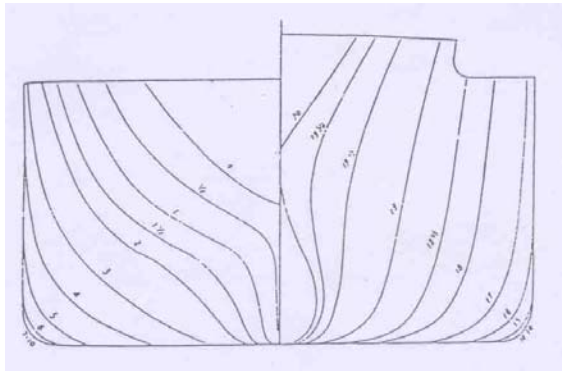

Fig. 1: Transverse Sections of FPSO

3. Description of Model

3.1 FPSO Model

The FPSO model was made in fiber reinforced plastic material with the transverse sections as shown in 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 366 N. The model was ballasted with additional weights of 415 N, 1052 N & 1319 N to achieve the 40%, 70% and 100% DWT respectively.

Fig.2: View of the Internal Turret Moored FPSO System

3.2 Internal Turret system

The internal turret system as shown in Fig.6 consists of

   (i)   Turret body
   (ii)   Bearing support structure
   (iii)   Mooring chain pipes
   (iv)   Load cell fixing plate
   (v)   Spider plate

The turret body was fabricated in PVC and perspex materials. The weather-vaning bearing arrangement was provided around the turret structure which was incorporated with mooring pipes to accommodate catenary chains in order to connect the FPSO model. The load cells were fixed at the top of the turret structure.

3.3 Mooring Chains

Steel chains connected with load cells were used to simulate the mooring line of the turret moored FPSO system. The steel chain of open link type with 0.3532 N/m for the model was selected based on the weight of the prototype mooring line.

3.4 Mooring Arrangement

Two mild steel angles of 50x50x5mm weighing 16 kg were selected for mooring purposes. In order to connect the mooring lines, holes were drilled in the angles which were firmly installed to the flume bed with wooden wedges. The angles were fixed at a distance of 4m from the turret center and this entire mooring arrangement simulates a catenary anchor leg mooring (CALM) system.

4. Experimental Investigation

Model tests were conducted in the wave flume for different loading conditions and different turret locations under regular waves in head sea condition. The present experimental investigation on FPSO model has been carried out with the following objectives.

      (a) To determine the mooring line forces.
      (b) To investigate the dynamic response.
      (c) To compare the dynamic performances, mooring line forces for different loading conditions with different turret locations.

4.1 Test Facility

The present experimental investigations were carried out in a 85m long, 2m wide and 2.7m deep wave flume in Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai. A wave maker is installed at one end of flume and the other end of flume is provided with an absorber which is combination of a parabolic perforated sheet and rubble mound below it to effectively absorb the deep water waves and shallow water waves respectively.

4.2 Experimental Set up

For the present study, the turret moored FPSO model was kept at a distance of 40m away from the flume wave maker and one wave gauge was fixed at distance of 9m from the model. The FPSO model was suitably ballasted to achieve the desired loading conditions *i.e.,* 40%, 70% and 100% DWT respectively. Two mooring chains are connected with load cells to measure the mooring line tension. The water depth was kept as 1.0m. The complete view of the internal turret moored FPSO system and the experimental setup are shown in Figs.2 & 3 respectively.
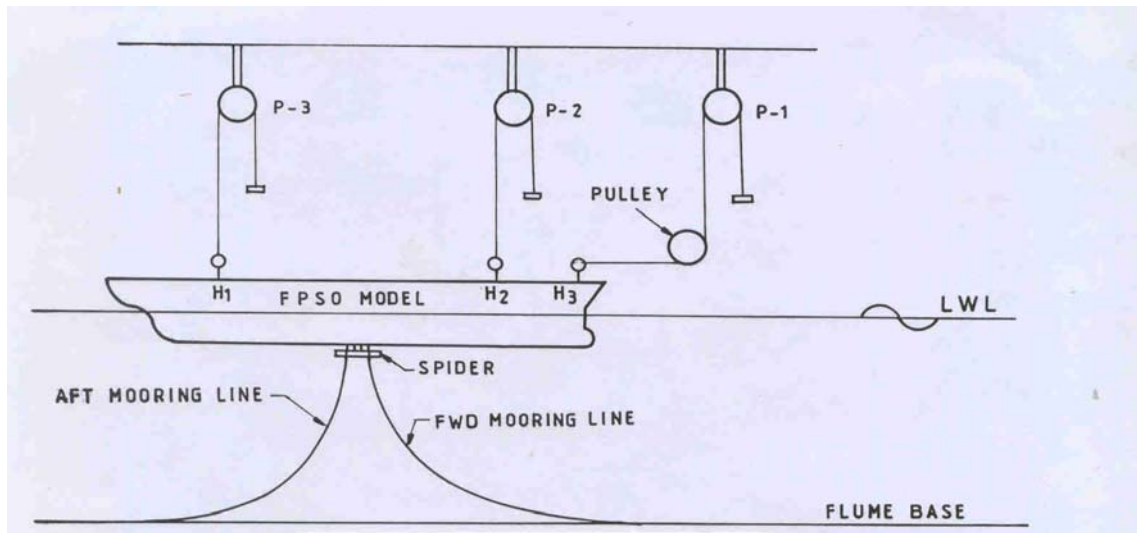

Fig. 3: Experimental Setup

4.3 Instrumentation

The water surface elevation was measured by means of wave gauge. The principle of varying conductivity with varying immersion of two electrodes is applied in the wave gauge for measurement. The electrodes are housed in a slim, streamline plastic profile with stainless steel armouring .The gauge was mounted on a support and can be fixed at any required depth. The wave gauge was calibrated by vertically raising and lowering in known incremental distances relative to the still water level and recording the corresponding analog output voltage from the wave amplifier. The calibration constant of the wave probe is calculated as 1volt = 18mm/volt. The motion response in the surge, heave and pitch directions were measured with three rotary type potentiometers. The rotary potentiometer is a device capable of measuring the linear displacement. The potentiometer has a pulley over which the thread from the hook on the model passes around and a counter weight is attached to the other

end of the thread. For measuring the surge motion, the thread was passed around an idler pulley before passing over the potentiometer. As the model is set into motion, the potentiometer pulleys begin to rotate and the output is measured in terms of the volts, which in turn is converted to displacement by multiplying with the calibration factor. The potentiometer is calibrated by rotating the pulley for a known number of rotations and measuring the corresponding voltage. 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 $\pm$ 10v. Tests were carried out to measure the motion response in regular head sea condition.
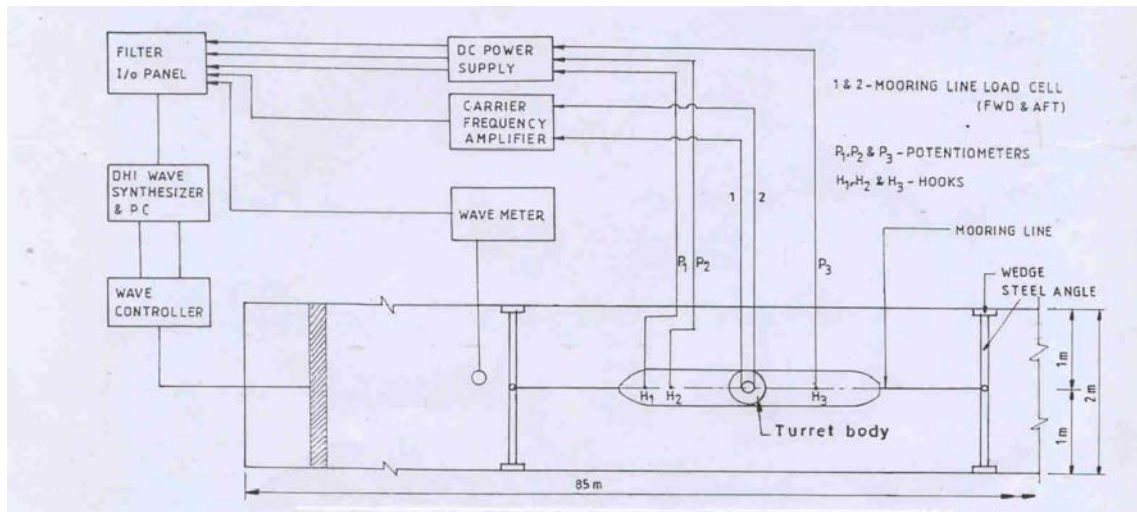

Fig. 4: Instrumentation of the Model

The forces of the mooring lines were measured using load cells. The load cells are designed so that the strain is proportional to the load being supported by the load cell. The forces in the mooring lines were measured using ring type load cells made of stainless steel ring of thickness 1.5mm,the load cell were fabricated with an outer diameter of 40mm.These load cells consists of a machined steel ring that is necked down at two diametrically opposite locations where it is instrumented with strain gauges to measure the deformation of the ring under the load. The calibration of these load cells were accomplished by loading the cells with a series of weight and recording the output through the data acquisition system. The strain for unit load is measured from the calibration curve. 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.

4.4 Test procedure
The experiments were carried out under regular waves for head sea condition with frequencies ranging from 0.55Hz to 1.25Hz in steps of 0.04Hz for a wave height of 50mm at constant water depth of 1m.Mooring lines were given initial pretension of 2N before starting the experiment. The incident wave height, forces in mooring lines and motion response of the model were obtained using the data acquisition system as shown in Fig.4. The test procedure was repeated for three loading conditions and different turret locations as shown in Fig.5. Typical time series of mooring line forces and motion response are shown in Fig 7.

5. Results and Discussion

(i) Motion Response
The dynamic response of the model in waves is reported as transfer function. This function gives the amplitude of rigid body motions normalized with the amplitude of the incoming wave as a function of wave frequency The ratio of response amplitude to the wave amplitude is reported as the Response Amplitude Operator (RAO) and it is plotted against 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 (rad / sec) and g is the acceleration due to gravity. The data analysis of the

model tests were carried out and the dynamic response of the FPSO system have been presented in the normalized form as detailed below:

Surge RAO = Surge amplitude / Wave amplitude
Heave RAO = Heave amplitude / Wave amplitude
Pitch RAO = Pitch amplitude / Wave slope

The variations of the motion response with wave frequency parameter for three loading conditions are shown in Figs.8, 9, & 10.
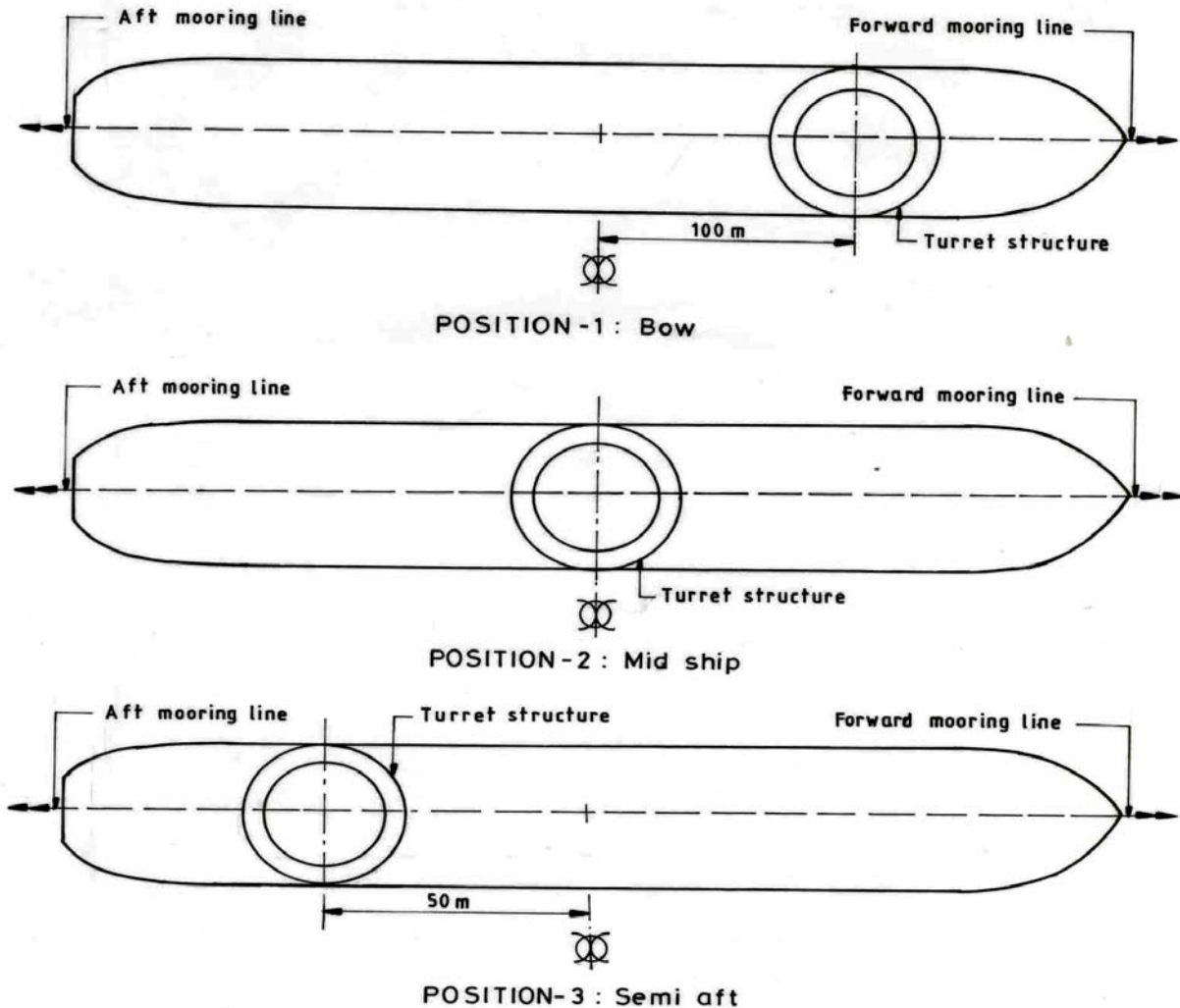
Fig. 5: Different Positions of Turret Structure of an Internal Turret Moored FPSO System

Turret Location : Forward Position

Surge RAO

The maximum surge RAO is observed as 0.2068 for 40%DWT, at ω_L =1.679 and it shows decreasing trend with increase in wave frequency and minimum surge RAO value is 0.0129 occurs at ω_L =8.502. For 70%DWT, the maximum surge RAO of 0.2217 is observed at ω_L = 1.679 and minimum surge RAO 0.0208 is observed at ω_L = 8.502. At 100%DWT, the maximum surge RAO of 0.2516 is observed at ω_L = 1.679 and minimum surge RAO value is 0.0349 occurs at ω_L =8.502. Among the three loading conditions, the maximum surge RAO of 0.2516

occurs in 100%DWT at ω_L =1.679. 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 18% and 12% less than that of 100 % DWT surge RAO respectively.
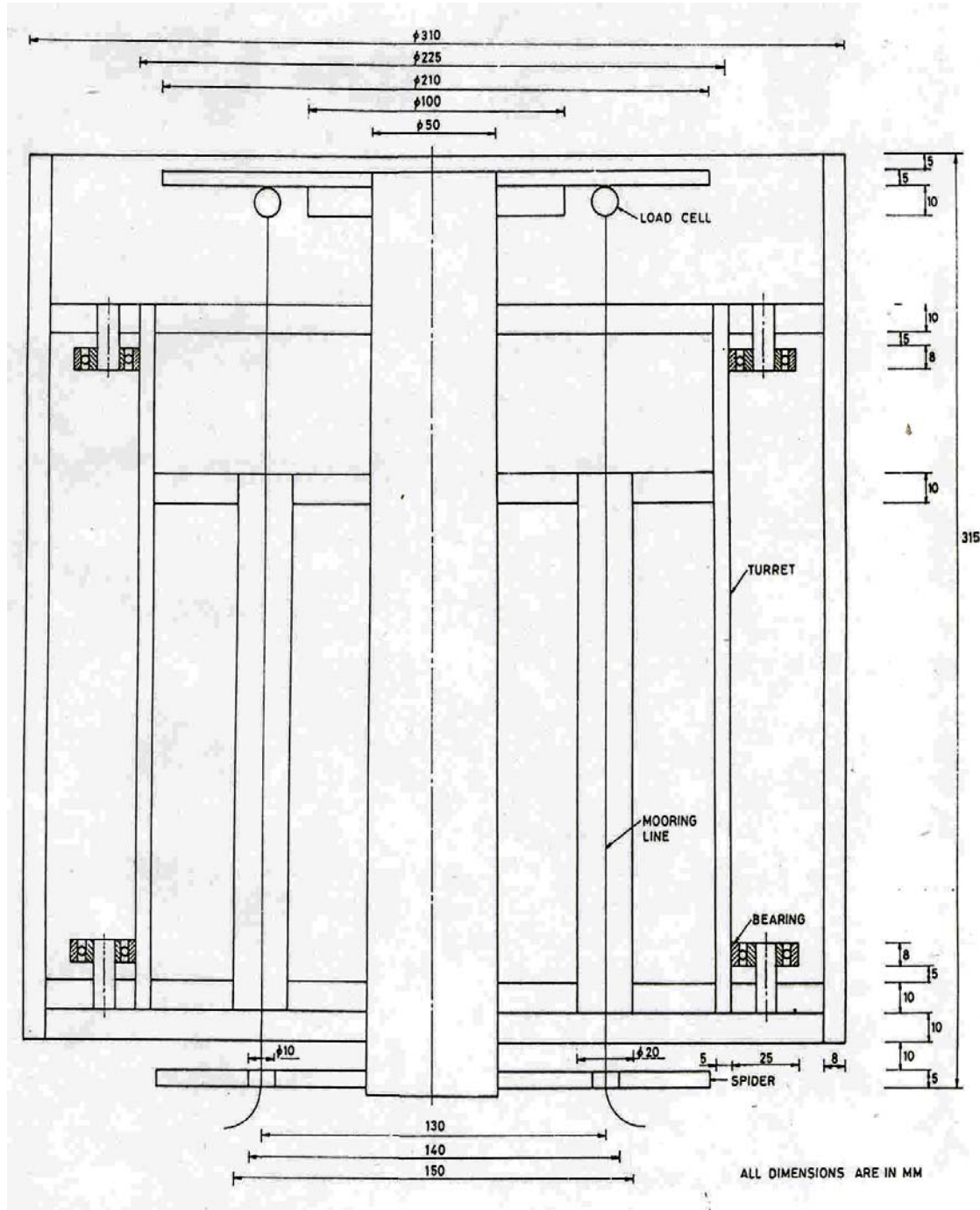

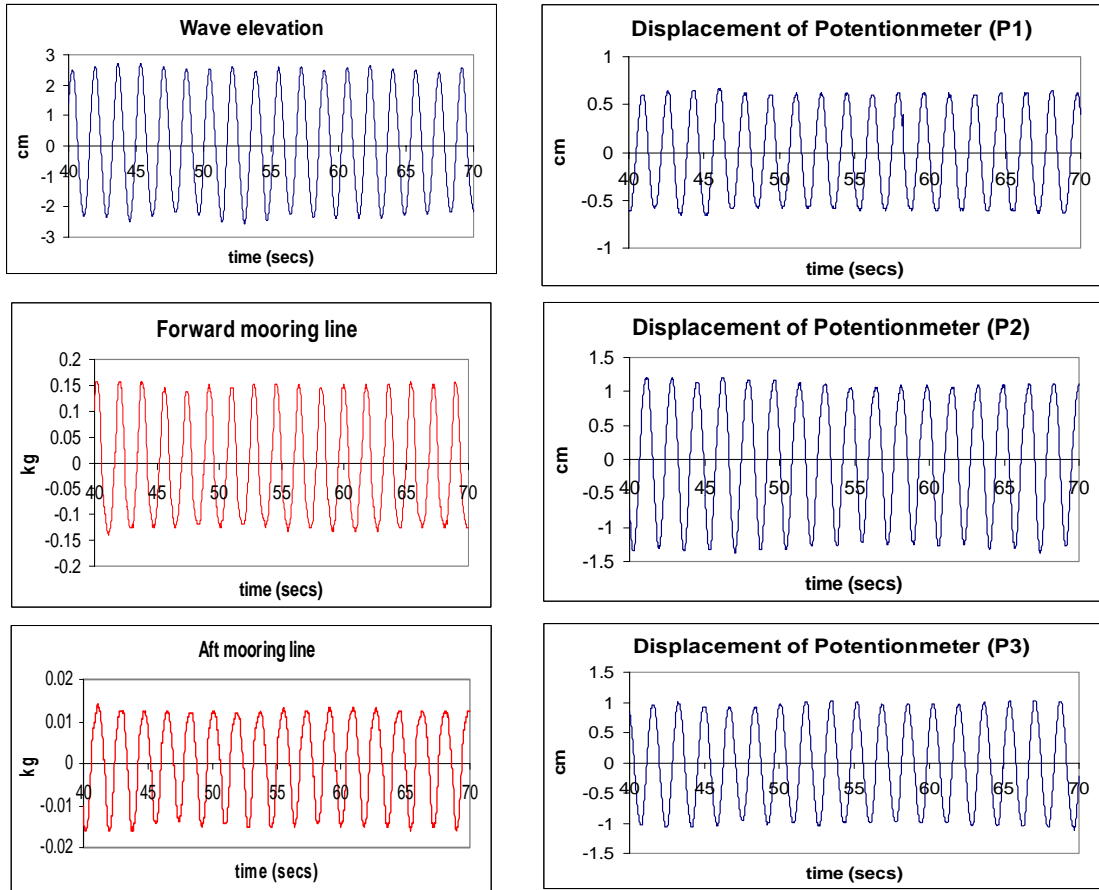**Fig. 6:** Details of Internal Turret

Fig. 7: Typical time series of wave elevation, motions and mooring line tension

Heave RAO

At 40%DWT, the maximum heave RAO is observed as 0.4416 at ω_L =3.779 and it shows increasing trend with a increase in wave frequency and minimum heave RAO value is 0.0591 occurs at ω_L =8.502. For 70%DWT, the maximum heave RAO of 0.4819 is observed at ω_L = 3.779 and minimum Heave RAO 0.0788 is observed at ω_L = 8.502. At 100% DWT the maximum heave RAO of 0.6525 is observed at ω_L = 3.779 and minimum heave RAO value is 0.0974 occurs at ω_L =8.502. Among the three loading condition the maximum heave RAO of 0.6525 occurs in 100%DWT at ω_L =3.779. 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 33% and 27% less than that of 100%DWT heave RAO respectively.

Pitch RAO

For 40%DWT, the maximum pitch RAO is observed as 0.3150 at ω_L =3.779 and it shows increasing trend with a increase of wave frequency, the minimum pitch RAO value is 0.0191 occurs at ω_L =8.502. At 70%DWT, the maximum pitch RAO of 0.3440 is observed at ω_L = 3.779and minimum pitch RAO of 0.02501 is observed at ω_L = 8.502. For 100% DWT the maximum pitch RAO of 0.4660 is observed at ω_L = 3.779 and minimum RAO value is 0.0310 occurs at ω_L =8.502. Among the three loading condition the maximum pitch RAO of 0.4660 occurs in 100%DWT at ω_L =3.779. 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 32% and 26% less than that of 100%DWT pitch RAO respectively.
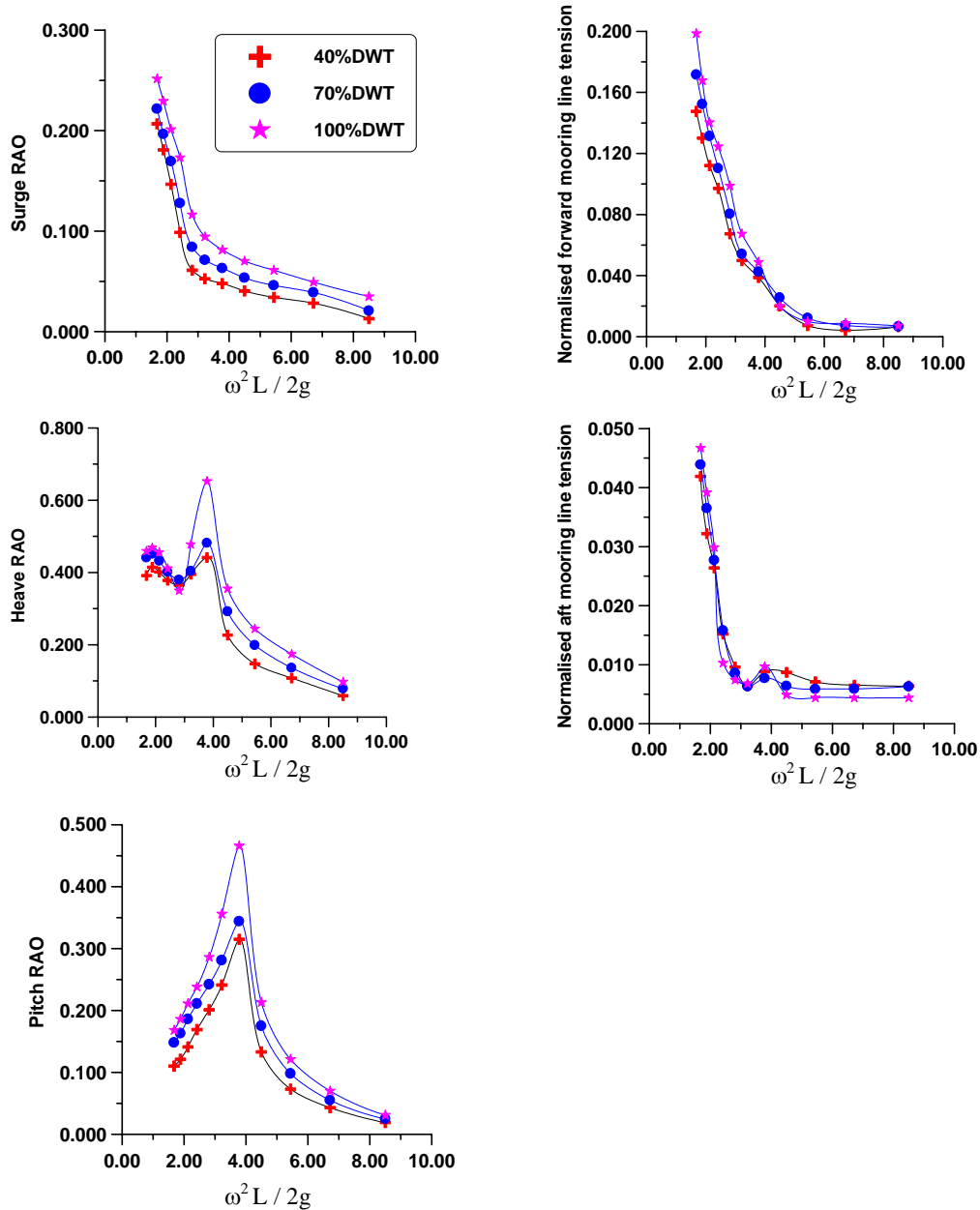
Fig. 8.: Normalized vessel motions and mooring line tension Vs non-dimensionalised wave frequency parameter for the forward position of the turret

Turret Location: Midship Position

Surge RAO

The maximum surge RAO is observed as 0.2657 for 40%DWT, at ω_L =1.679 and it shows decreasing trend with increase in wave frequency and minimum surge RAO value is 0.0231 occurs at ω_L =8.502. For 70%DWT, the maximum surge RAO of 0.3126 is observed at ω_L = 1.679 and minimum surge RAO 0.0314 is observed at ω_L = 8.502. At 100%DWT, the maximum surge RAO of 0.3479 is observed at ω_L = 1.679 and minimum surge RAO

value is 0.0447 occurs at ω_L =8.502. Among the three loading conditions, the maximum surge RAO of 0.3479 occurs in 100%DWT at ω_L =1.679. 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 24% and 11% less than that of 100 % DWT surge RAO respectively.
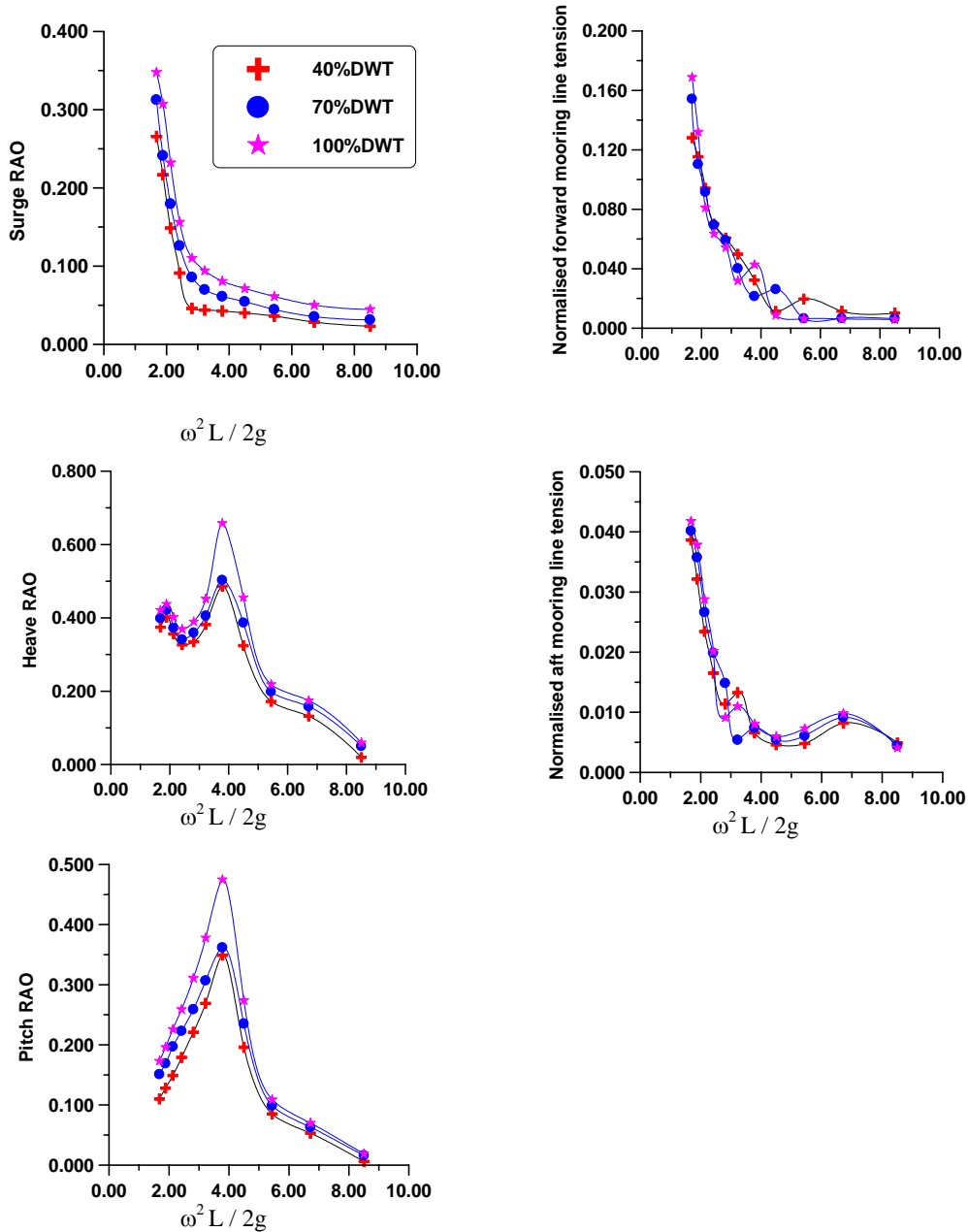

Fig. 9: Normalized vessel motions and mooring line tension Vs non-dimensionalised wave frequency parameter for the mid ship position of the turret

Heave RAO

At 40%DWT, the maximum heave RAO is observed as 0.4860 at ω_L =3.779 and it shows increasing trend with a increase in wave frequency and minimum heave RAO value is 0.1946 occurs at ω_L =8.502. For 70%DWT, the maximum heave RAO of 0.5030 is observed at ω_L = 3.779 and minimum Heave RAO 0.0498 is observed at ω_L = 8.502. At 100% DWT the maximum heave RAO of 0.6580 is observed at ω_L = 3.779 and minimum heave RAO value is 0.0594 occurs at ω_L =8.502. Among the three loading condition the maximum heave RAO of 0.6580 occurs in 100%DWT at ω_L =3.779. 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 27% and 24% less than that of 100%DWT heave RAO respectively.

Pitch RAO

For 40%DWT, the maximum pitch RAO is observed as 0.3490 at ω_L =3.779 and it shows increasing trend with increase of wave frequency, the minimum pitch RAO value is 0.0060 occurs at ω_L =8.502. At 70%DWT, the maximum pitch RAO of 0.3620 is observed at ω_L = 3.779 and minimum pitch RAO of 0.0160 is observed at ω_L = 8.502. For 100% DWT the maximum pitch RAO of 0.4750 is observed at ω_L = 3.779 and minimum RAO value is 0.0190 occurs at ω_L =8.502. Among the three loading condition the maximum pitch RAO of 0.4750 occurs in 100%DWT at ω_L =3.779. 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 27% and 24% less than that of 100%DWT pitch RAO respectively.

Turret Location: Semi- aft Position

Surge RAO

The maximum surge RAO is observed as 0.2783 for 40%DWT, at ω_L =1.679 and it shows decreasing trend with increase in wave frequency and minimum surge RAO value is 0.0126 occurs at ω_L =8.502. For 70%DWT, the maximum surge RAO of 0.3257 is observed at ω_L = 1.679 and minimum surge RAO 0.0194 is observed at ω_L = 8.502. At 100%DWT, the maximum surge RAO of 0.3594 is observed at ω_L = 1.679 and minimum surge RAO value is 0.02936 occurs at ω_L =8.502. Among the three loading conditions, the maximum surge RAO of 0.3594 occurs in 100%DWT at ω_L =1.679. 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 23% and 9% less than that of 100 % DWT surge RAO respectively.

Heave RAO

At 40%DWT, the maximum heave RAO is observed as 0.5429 at ω_L =3.779 and it shows increasing trend with increase in wave frequency and minimum heave RAO value is 0.0799 occurs at ω_L =8.502. For 70%DWT, the maximum heave RAO of 0.5868 is observed at ω_L = 3.779 and minimum Heave RAO 0.0942 is observed at ω_L = 8.502. At 100% DWT the maximum heave RAO of 0.6963 is observed at ω_L = 3.779 and minimum heave RAO value is 0.1048 occurs at ω_L =8.502. Among the three loading condition the maximum heave RAO of 0.6963 occurs in 100%DWT at ω_L =3.779. 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 23% and 16% less than that of 100%DWT heave RAO respectively.

Pitch RAO

The maximum pitch RAO is observed as 0.3901 for 40%DWT, at ω_L =3.779 and it shows increasing trend with increase of wave frequency, the minimum pitch RAO value is 0.0250 occurs at ω_L =8.502. For 70%DWT, the maximum pitch RAO of 0.4190 is observed at ω_L = 3.779 and minimum pitch RAO of 0.0301 is observed at ω_L = 8.502. At 100% DWT the maximum pitch RAO of 0.5001 is observed at ω_L = 3.779 and minimum RAO value is 0.0330 occurs at ω_L =8.502. Among the three loading condition the maximum pitch RAO of 0.5000 occurs in 100%DWT at ω_L =3.779. 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 22% and 17% less than that of 100%DWT pitch RAO respectively.
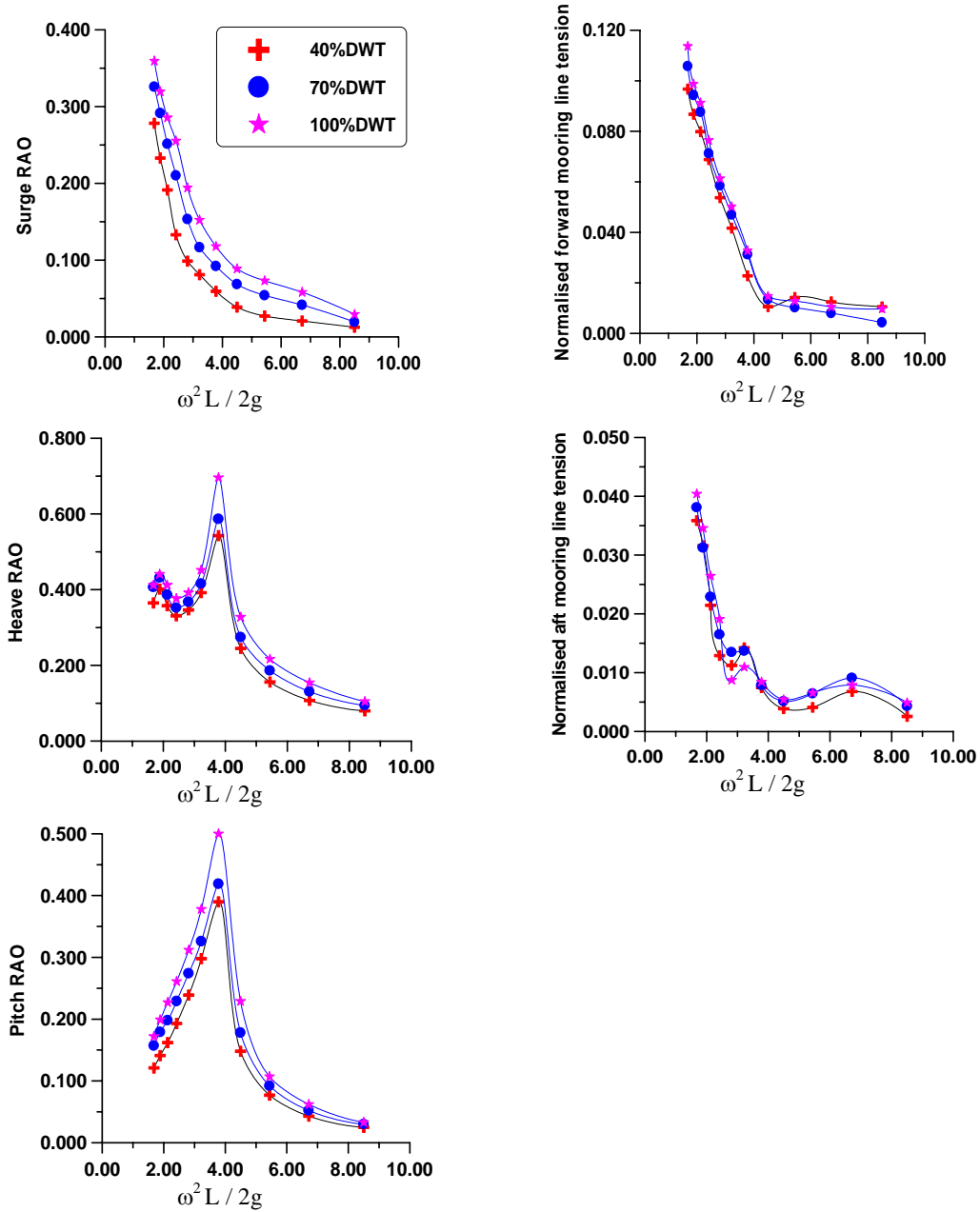
Fig. 10: Normalized vessel motions and mooring line tension Vs non-dimensionalised wave frequency parameter for the semi - aft position of the turret

(ii) Mooring Line forces

The measured tension in the two mooring lines under three loading conditions are normalized with the breaking strength of the mooring chain. The normalized mooring line tension is plotted against the nondimensionalised 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 (rad / sec) and g is the acceleration due to gravity. The comparison of mooring line forces for three

loading conditions *i.e.,* 40%DWT, 70%DWT and 100%DWT, of the FPSO system has been presented as shown in Figs. 8, 9 & 10.

Turret Location: Forward Position

Forward mooring line

The maximum normalised line tension is observed as 0.1476 for 40%DWT, at ω_L =1.679 and the minimum mooring line tension value is 0.0066 occurs at ω_L =8.502. For 70%DWT, the maximum line tension of 0.1716 is observed at ω_L =1.679 and minimum mooring line tension of 0.0062 is observed at ω_L = 8.502. At 100%DWT, the maximum line tension of 0.1986 is observed at ω_L = 1.679 and the minimum mooring line tension value is 0.0071 occurs at ω_L =8.502. Among the three loading conditions the maximum mooring force occurs at 100%DWT at ω_L = 1.679. By comparing the line tension of 40%DWT and 70%DWT with the maximum line tension corresponding to100%DWTat the same wave frequency *i.e.,* ω_L = 1.679, they are 26% and 14% less than that of 100%DWT respectively.

Aft mooring line

At 40%DWT, the maximum normalised line tension is observed as 0.0419 at ω_L =1.679 and the minimum mooring line tension value is 0.0064 occurs at ω_L =3.219. For 70%DWT, the maximum line tension of 0.0439 is observed at ω_L = 1.679 and minimum mooring line tension of 0.0063 is observed at ω_L = 3.219. At 100%DWT, the maximum line tension of 0.0467 is observed at ω_L = 1.679 and the minimum mooring line tension value is 0.0044 occurs at ω_L =5.441. Among the three loading conditions the maximum mooring force occurs at 100%DWT at ω_L = 1.679. By comparing the line tension of 40%DWT and 70%DWT with the maximum line tension corresponding to100%DWTat the same wave frequency *i.e.,* ω_L = 1.679, they are 12% and 6% less than that of 100%DWT respectively.

Turret Location: Midship Position

Forward mooring line

The maximum normalized line tension is observed as 0.1281 for 40%DWT, at ω_L =1.679 and the minimum mooring line tension value is 0.0102 occurs at ω_L =6.717. For 70%DWT, the maximum line tension of 0.1543 is observed at ω_L =1.679 and minimum mooring line tension of 0.0065 is observed at ω_L = 5.441. At 100%DWT, the maximum line tension of 0.1689 is observed at ω_L = 1.679 and the minimum mooring line tension value is 0.0059 occurs at ω_L =8.502. Among the three loading conditions the maximum mooring force occurs at 100%DWT at ω_L = 1.679. By comparing the line tension of 40%DWT and 70%DWT with the maximum line tension corresponding to100%DWT at the same wave frequency *i.e.,* ω_L = 1.679, they are 24% and 9% less than that of 100%DWT respectively.

Aft mooring line

At 40%DWT, the maximum normalized line tension is observed as 0.0386 at ω_L =1.679 and the minimum mooring line tension value is 0.0046 occurs at ω_L =4.497. For 70%DWT, the maximum line tension of 0.0402 is observed at ω_L = 1.679 and minimum mooring line tension of 0.0044 is observed at ω_L = 4.497. The maximum line tension of 0.0418 is observed for 100%DWT, at ω_L = 1.679 and the minimum mooring line tension value is 0.0041 occurs at ω_L =3.779. Among the three loading conditions the maximum mooring force occurs at 100%DWT at ω_L = 1.679. 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 = 1.679, they are 8% and 4% less than that of 100%DWT respectively.

Turret Location: Semi- aft Position

Forward mooring line

The maximum normalised line tension is observed as 0.09675 for 40%DWT, at ω_L =1.679 and the minimum mooring line tension value is 0.0105 occurs at ω_L =4.497. For 70%DWT, the maximum line tension of 0.1058 is observed at ω_L =1.679 and minimum mooring line tension of 0.0041 is observed at ω_L = 5.441. At 100%DWT, the maximum line tension of 0.1137 is observed at ω_L = 1.679 and the minimum mooring line tension value is 0.0097 occurs at ω_L =8.502. Among the three loading conditions the maximum mooring force occurs at

100%DWT at $\omega_L = 1.679$. 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.,* $\omega_L = 1.679$, they are 15% and 7% less than that of 100%DWT respectively.

Aft mooring line

At 40%DWT, the maximum normalised line tension is observed as 0.0358 at $\omega_L = 1.679$ and the minimum mooring line tension value is 0.0025 occurs at $\omega_L = 8.502$. For 70%DWT, the maximum line tension of 0.0381 is observed at $\omega_L = 1.679$ and minimum mooring line tension of 0.0043 is observed at $\omega_L = 8.502$. The maximum line tension of 0.0404 is observed for 100%DWT, at $\omega_L = 1.679$ and the minimum mooring line tension value is 0.0049 occurs at $\omega_L = 8.502$. Among the three loading conditions the maximum mooring force occurs at 100%DWT at $\omega_L = 1.679$. 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.,* $\omega_L = 1.679$, they are 12% and 6% less than that of 100%DWT respectively.

The comparisons of motion response and mooring line forces for different loading conditions are presented in tables 2 & 3.

Table 2: Normalized dynamic response for three turret locations with different loading conditions

Description	FORWARD POSITION			MIDSHIP POSITION			SEMI - AFT POSITION		
	40%DWT	70% DWT	100% DWT	40% DWT	70% DWT	100% DWT	40%DWT	70%DWT	100%DWT
SURGE RAO	0.2068	0.2217	0.2516	0.2657	0.3126	0.3479	0.2783	0.3257	0.3596
HEAVE RAO	0.4416	0.4819	0.6525	0.4860	0.5030	0.6580	0.5429	0.5868	0.6963
PITCH RAO	0.3150	0.3440	0.4660	0.3490	0.3620	0.4750	0.3900	0.4190	0.5000

Table 3: Normalized mooring line forces for three turret locations with different loading conditions

Description	FORWARD POSITION			MIDSHIP POSITION			SEMI - AFT POSITION		
	40%DWT	70% DWT	100% DWT	40% DWT	70% DWT	100% DWT	40%DWT	70%DWT	100%DWT
Mooring Line(FWD)	0.1476	0.1716	0.1986	0.1281	0.1543	0.1689	0.0967	0.1058	0.1137
Mooring Line(AFT)	0.0419	0.0439	0.0467	0.0386	0.0402	0.0418	0.0358	0.0381	0.0404

Conclusions

From the analysis of the model test results of the internal turret moored FPSO system by CALM with two mooring lines, it is observed that:

(i)   The mooring forces are not equally shared by forward and aft mooring lines for all loading conditions *i.e.,* 40%DWT, 70%DWT and 100%DWT for different positions of the turret. It is observed that the reduction in tension is about 40% and 15% for the forward and aft mooring line respectively as the turret is shifted from forward position to semi-aft position for all the loading conditions.

(ii)   The tension in the forward mooring lines is 3 to 7 times more than the tension in the aft line for all loading conditions.

(iii)   Surge and pitch motion increase with the increase of DWT for all loading conditions for all turret positions.

(iv)   For all loading conditions, there is decrease in surge motion of about 30% for the forward position of the turret in comparison with mid ship and semi- aft position of the turret.

(v)   Heave motions follows the same trend of increase in motion with the increase of DWT for all positions of the turret.

(vi)   Pitch motion is decreased by about 20% when the turret position is shifted from semi- aft position to forward position for the same loading condition.

Based on the above conclusions, it is recommended that among the three turret locations, the forward turret position is the best suited position for the internal turret moored FPSO system, so as to have favourable working environment at all loading conditions which is the prime functional requirement of the turret moored FPSO system, even the maximum motion response of the FPSO system occurs at full loaded condition. Hence, it is finally concluded that the internal turret moored FPSO with CALM system is to be designed for full loaded condition for its safe and efficient operation.

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