OTC 11914

Global Analysis of the Terra Nova FPSO Turret Mooring System

Arun S. Duggal and Caspar N. Heyl, FMC SOFEC, and George P. Vance, ExxonMobil

Abstract

This paper describes the global mooring analysis conducted for the Terra Nova FPSO, located on the Grand Banks, offshore Eastern Newfoundland, Canada. The FPSO has a disconnectable internal turret mooring system that must withstand the 100-year storm environment, and be disconnectable to avoid collision with large icebergs.

The global analysis of the FPSO vessel and mooring system focuses on the response of the system in storm conditions, and during offloading, disconnect and reconnect operations. The analysis was performed using sophisticated analytical and numerical techniques, integrated with a comprehensive model test program primarily for verification of the analysis. As the Terra Nova FPSO is the first such platform to operate in an iceberg region, a focus of the analysis was in studying the interaction of pack ice and icebergs with the FPSO system.

The methodology used to analyze the FPSO system is outlined in this paper and some key results are presented.

Introduction

The Terra Nova FPSO will be located in approximately 95 meters water depth on the Grand Banks off the East Coast of Newfoundland, Canada. The region has a harsh environment, much like the Northern North Sea, with intense storms occurring frequently in winter. In addition, there is sea ice excursion into the region, including pack ice and icebergs.

The FPSO system consists of a new-build FPSO vessel and a disconnectable turret with a thruster-assisted, 9-leg mooring system. The turret supports 14 risers and 5 umbilicals servicing wellheads in four or more glory holes. The internal turret mooring system has been designed to maintain station in the 100-year storm environment, and to be disconnectable to avoid an approaching iceberg on a collision course. Once the FPSO disconnects, the mooring and riser system is supported by a spider buoy that has an equilibrium depth of 35 meters below sea level.

The global analysis of an FPSO system requires detailed knowledge of the environment, vessel characteristics, and the mooring system design. The analysis of the Terra Nova system has further complications due to the use of an automatically controlled thruster system to assist the mooring, and the disconnect and reconnect operations. The following sections briefly describe the methodology used to study the combined FPSO vessel and mooring system response, and present a few results to illustrate the performance of the system, and the accuracy of the analysis.

Stationkeeping Design Basis

The mooring system has been designed to meet or exceed the requirements of Lloyd's Register (References 1 and 2) for a thruster-assisted, permanent mooring system. The design basis for the FPSO global analysis is summarized below:

- The Terra Nova FPSO must be moored on station in a 100-year storm, requiring the turret mooring system to be designed for the 100-year environment. The mooring system can depend on the full capability of the thruster system (25 MW).
- In seastates up to the 1-year storm the mooring system can only utilize the heading control mode of the thruster system, with a maximum peak power demand of 10 MW.
- The turret mooring system is required to be disconnectable to avoid collisions with icebergs greater than 100,000 MT. There are two conditions placed on the disconnectability of the system. A *controlled* disconnect must be accomplished in seastates up to the 1-year ice season storm (7.4 meters significant) in less than 4 hours, with all risers flushed and de-pressurized. The system must also provide an *emergency* disconnect that must be accomplished in 15 minutes or less.
- The FPSO is required to reconnect to the mooring and risers in seastates up to 2.1 meters significant with no external assistance.
- The design life of the system is 25 years.

The design basis has resulted in the design of the first disconnectable turret mooring system that is required to stay connected in a severe 100-year storm environment, and be disconnectable to avoid possible collisions with icebergs only. This has resulted in a disconnectable turret system that can withstand the large loads transmitted through the turret in a 100-year environment, requiring the development of several specialized components to provide the high load carrying capacity and safety. This is in contrast to disconnectable systems that have been employed in the South China Sea that disconnect for typhoons, resulting in reduced environmental criteria and the resulting loads for the turret mooring design. The stringent disconnect and reconnect criteria have also resulted in the design of a very sophisticated and automated disconnectable turret mooring system.

Design Environmental Criteria

The environment at the Terra Nova site is one of the harshest in the world with a 100-year significant wave height of 16 meters, and 1-hour mean wind speeds of 40 m/s. The site is situated in "iceberg alley" where large icebergs from Greenland and Ellesmore Island drift south with the Labrador current. Surveys have shown the presence of iceberg scour marks on the seabed, and statistics indicate that the site could see as many as 66 large icebergs in a single season (April – July). Table 1 provides a summary of the design storm conditions for both the 1-year and 100-year return intervals.

Compared to the Gulf of Mexico and the North Sea, the amount of environmental data available for the Grand Banks is limited, with very little knowledge on wave direction. This has led to a lot of uncertainty in the development of the design environmental criteria and has required the robust design of the FPSO mooring system to account for unforeseen environmental conditions.

FPSO Vessel and Turret Mooring System

FPSO Vessel. The new build vessel is specifically designed for the harsh conditions on the Grand Banks. The 960,000 bbl storage vessel has an LBP of 277 meters, a beam of 45.5 meters, and a depth of 28.2 meters. At the full load condition the vessel has an average draft of 18.6 meters, with a displacement of 193,000 MT. The hull is ice-strengthened to site specific criteria, and the bow and freeboard elevations have been designed to minimize any greenwater on the deck.

The vessel has five azimuthing thrusters rated at 5 MW each, with two mounted at the bow and three at the stern. The thrusters are used to assist the mooring system when the vessel is on station, to control and maneuver the vessel during the disconnect operation, and to position the vessel during the reconnect operation. Details on the vessel design and construction are provided in Reference 3.

The thruster system controls the FPSO position by providing surge, sway and yaw (heading) control by introducing "stiffness" and "damping" in each mode. The control system, based on a Kalman filter algorithm, uses two redundant position-monitoring systems to estimate turret position with respect to FPSO center, and obtains vessel heading information from gyro compasses. The automatic control system then uses the thruster system to provide the desired control, based on input from the operator. The thruster system with its automatic control system has been designed to meet Lloyd's Register class PM(T3) (References 1 and 2).

Turret Mooring System. The disconnectable internal turret mooring system is located 74 meters aft of the forward perpendicular of the vessel. The turret diameter varies from 12 meters at the main deck to 21.5 meters at the keel, with a total height of approximately 60 meters. The turret has two bearing systems: a lower bearing located near the vessel keel that reacts the horizontal loads imparted by the mooring, and an upper bearing located at the main deck elevation to react all vertical loads, moments, and the residual horizontal loads. The turret has a disconnectable spider buoy that supports the all-chain mooring system, and the nineteen risers and umbilicals. Figure 1 provides a general arrangement of the FPSO vessel and mooring system.

The spider buoy is connected to the lower turret using a single pre-tensioned connector that can be released hydraulically, allowing the spider buoy to free-fall to the desired subsurface position. The spider buoy has a diameter of 17 meters, and net buoyancy of 450 MT. The risers are connected to flanges at the bottom of the buoy, and quick-connect/quick-disconnect valves are provided at the spider buoy-lower turret interface. A schematic of the turret system is provided in Figure 2.

The 9 anchor legs are arranged in three groups of 3 anchor legs each, with each group 120 degrees apart. Each anchor leg consists of studless Grade R4 chain (146 mm) terminating in an anchor pile. The mooring system is designed with a heavier section of chain ("excursion limiter") at the touchdown point that is optimized to reduce vessel offsets and mooring loads. As described in the design basis the mooring system requires assistance from the thruster system on the vessel in the storm environments.

The 14 risers and 5 umbilicals are arranged at the turret in three groups in between the anchor leg groups, using a pliant wave configuration. The risers range from 10-inch production and water injection risers to 5-inch gas lift risers.

Global Analysis Methodology

The shallow water depth, coupled with the harsh environmental conditions, make the global analysis of a highly non-linear system like Terra Nova very challenging. Accounting for the dynamics of a thruster-assisted mooring system further complicates the global analysis.

The FPSO system has been analyzed by integrating a detailed analytical and numerical study of the system response with a comprehensive model test program. The simulation of the FPSO vessel and mooring system used both frequency-domain and time-domain methods to develop the system response, mooring system performance, and turret-vessel interface loads. The methodology used to perform the numerical simulations follows the general guidelines described in the API RP 2SK (Reference 4). A large number of sensitivity studies were performed using the frequency-domain tools, and detailed finite element models were built to study the turret loads for the governing design cases. The model test program was primarily developed to verify the various stages of the analysis, and to provide input data for use in the analysis, e.g., wind load coefficients, vessel hull characteristics, and pack ice loads.

The global analysis of the FPSO system focused on four scenarios:

1. Response of the FPSO system in the 1-year and 100-year design environments (vessel connected to mooring with thruster-assist). This required the use of a coupled non-linear vessel-mooring simulation that also modeled the dynamics of the thruster system assisting the mooring.
2. Detailed analysis of the spider buoy disconnect operation and the dynamics of the spider-buoy free-fall to the design depth.
3. Analysis of the submerged spider buoy, mooring, and riser system for the design seastates to study buoy motions and the associated mooring and riser dynamics, to primarily aid in the buoy and riser design.
4. Analysis of the reconnection operation studying the vessel-buoy dynamics during retrieval and the loads on the retrieval system, and at the buoy-turret interface.

Analytical and Numerical Modeling

The harsh environment, shallow water depth, and the non-linear nature of the FPSO mooring system, results in a challenging mooring system to analyze and design. The wave drift forces and damping, and the wave-frequency motions of the vessel have to be computed accurately, fully accounting for the effects of the shallow water and current. The stiff mooring system has a low level of critical surge damping, resulting in large low-frequency motions. The non-linearity of the mooring system implies small variations in vessel offsets can result in large variations in mooring system loads. Therefore the global analysis of such a system must be very comprehensive with input parameters being determined as accurately as possible, and the design of the turret mooring system should be sufficiently robust.

The vessel hull was modeled using a higher-order boundary element method diffraction program to provide both the quadratic transfer functions and response amplitude operators (RAOs) of the vessel for three load conditions: full, mid, and ballast. The wind and current load coefficients for the specific Terra Nova hull form and topsides layout were obtained from wind tunnels tests conducted on a 1:200 scale model.

The majority of the global analysis was performed with a proprietary frequency-domain analysis tool that simulates the highly non-linear dynamics of a turret-moored vessel with multi-element mooring lines and thruster assistance. The frequency-domain tool was used to perform an extensive sensitivity analysis of the FPSO system to various environmental and system parameters, resulting in the design of an optimum mooring system and the identification of a finite number of design cases for more detailed analysis. These cases were then studied using time-domain tools to provide detailed estimates of the mooring loads on the turret structure, and to analyze the effectiveness of the thruster-assist system in maintaining vessel heading and position.

Detailed finite element models were also used to study the transient response of the buoy-mooring-riser system after disconnect, and the steady state response of the system after the buoy reached its equilibrium depth. This provided information for the design of the riser system, including interaction with the seabed and estimates of minimum bend radius. The reconnect of the buoy to the FPSO was analyzed using a finite element model that included the buoy-vessel dynamics during the retrieval process, the load on the retrieval equipment, and the buoy-turret interaction. This analysis allowed the optimization of the reconnect equipment and operation. Similar models were also developed to perform all the detailed installation engineering of the spider buoy and mooring system, installed on the Grand Banks in late spring 1999.

Model Test Program

The model test program for the Terra Nova FPSO was primarily developed to provide sufficient data to verify the analytical and numerical analyses of the global FPSO response to the design environment. The model test program was also used to provide accurate estimates of wind, current and ice loads on the FPSO as input for the global analysis. The model test program was structured as follows:

Wind Tunnel Tests. The wind tunnel tests were conducted to provide estimates of the wind and current loads on the FPSO as a function of relative heading. The results were used as input for the global analysis of the system, and are also utilized by the automatic control system on the actual vessel as input for the wind feed-forward mode. The wind tunnel tests were conducted at the Danish Maritime Institute.

Resistance and Propulsion Tests. These tests were conducted at a scale of 1:27 to study the free-sailing characteristics and maneuverability of the new build hull. The tests were conducted at the Institute for Marine Dynamics (IMD), Newfoundland.

Pack Ice Tests. These tests were conducted in the ice basin at IMD with the 1:27 scale model of the hull mounted on a horizontal mooring with the desired stiffness. The vessel was towed through model pack ice at various speeds, simulating the movement of pack ice by the moored vessel. The tests were conducted for various floe sizes, thicknesses, and surface concentrations to provide an estimate of the pack ice and vessel interaction, and total loads on the mooring system.

Vessel Response Tests. These tests studied the vessel response and the greenwater phenomenon as a function of relative wave heading. The results from these tests were used to verify the computed vessel RAOs and to provide a detailed description of the relative wave elevation and the greenwater phenomenon. The tests were conducted at Marintek, Norway and IMD.

Survival Environment Tests. The FPSO system response and mooring loads were evaluated for a selection of the design environments. The thruster system was also modeled and controlled by a control system similar to the prototype. The results from these tests were primarily used to verify the global analysis, including the performance of the thruster-assist system. In addition, a series of tests were conducted to study the impact of a 100,000 MT iceberg, and a 3,000 MT bergy bit with the FPSO to verify that the mooring loads and local hull pressures were within the bounds estimated from the analysis. The tests were conducted at Marintek and IMD.

Disconnect and Reconnect Tests. These tests studied the disconnect and reconnect dynamics between the buoy and the vessel, and to study the thruster system performance during these operations. Tests were conducted to study the free-fall of the spider buoy in the design environments, focusing on the separation between the vessel and the buoy, and the maximum dive depth. The reconnect tests focused on the dynamics between the buoy and the vessel while the buoy was being retrieved and the loading on the retrieval equipment. Results from these tests were compared against results from the detailed numerical simulations conducted. The tests were conducted at IMD.

Results from the Global Analysis of the FPSO

Due to space limitations, only a few examples of the results obtained from the various stages of the global analysis and mooring design process are presented. These examples illustrate the complexity of the system, the detail and accuracy of the numerical simulations, and the integration of the results from the model test program in the final design of the system.

Turret Location on Vessel. An effort was made during the preliminary engineering phase of the project to optimize the location of the turret based on the requirements of the turret mooring system, the vessel, the location of the accommodations, and overall project levels of safety. This required a detailed integrated engineering effort between the designers of the vessel, the turret mooring system, and the risers.

From a mooring perspective, the optimum turret location is near the bow of the vessel, giving the vessel the maximum yaw stability for passive weathervaning. However, the vertical motions at the turret increase with an increase of turret distance from midships (due to the combined heave and pitch of the vessel), resulting in larger vertical motions for the design of the riser system. As the turret is moved towards midships the passive weathervaning stability decreases. To illustrate this point, the stable equilibrium heading in a collinear environment for a vessel with a turret midships is with its beam into the waves. However, the use of a thruster system to provide heading control can improve the weathervaning ability of the vessel with a turret at a non-optimum location for passive weathervaning.

Figure 3 provides a schematic of the turret location design process. The horizontal axis represents the turret location as a percentage of LBP from midships. The left vertical axis provides an estimate of the vessel equilibrium heading as a function of turret location The right vertical axis represents the vertical motion at the turret, expressed as a percentage of the heave at the vessel CG. The dashed arrows illustrate the general range of feasibility for the riser system, passive mooring system, and mooring with thruster-assistance.

As shown by Figure 3 the vertical motion of the turret increases with the distance from midships, and at some distance the riser system feasibility becomes an issue. With the turret located near the bow of the vessel, the equilibrium heading is 0 degrees (into the weather). When the turret is located at midships the equilibrium heading approaches 90 degrees (beam-on to weather). Placing the turret more that 20% LBP aft of the forward perpendicular typically results in a passive mooring concept reaching its limit of feasibility. However, the feasibility range can be extended if active heading control provided by a thruster system is provided as shown in the figure.

Due to the presence of the thruster system on the vessel, the challenge in developing a feasible riser system, and the desire to place the accommodations forward, the turret for the Terra Nova FPSO was placed 74 meters aft of FP (27% LBP). This resulted in the requirement for heading control in all large seastates to ensure an optimum vessel heading.

Mooring System Characteristics. The 3X3 grouped mooring system has been used with success for several shallow water FPSO systems. An interesting feature of the mooring system is the directional sensitivity of the restoring characteristics. This is illustrated in Figure 4 where isolines of vessel offset and anchor leg tension are presented as a function of orientation with respect to the mooring system. The behavior is due to the characteristic of a grouped mooring system that is stiff when forces are applied in-line with an anchor leg group and is much softer for forces applied between groups. The mooring system has been designed such that the offset requirement (20 – 35 meters) for the riser design is met for all environments and directions.

FPSO System Sensitivity Analysis. As described in the previous section a detailed analysis was performed to study the sensitivity of the FPSO system to various environmental and system parameters. Figure 5 presents a summary of results showing the sensitivity of the system to wave spectral peak period and peakedness parameter for a given significant wave height. It is seen that anchor leg tensions and turret loads are fairly insensitive to the parameters studied while vessel offset and wave-frequency motions show larger variations.

Similar parametric studies were performed to develop the design cases that would provide the maximum vessel motions and offsets, and anchor leg and turret loads. This was performed for both the intact and single component damage cases for both the mooring and thruster system. In all a total of 64 design cases were developed that were used to provide the final design loads for the system.

Survival Environment Response and Verification. Tables 2(a) and 2(b) compare the results obtained from numerical simulations and model tests for a few key design parameters for the turret mooring system in the 100-year storm environment. Table 2(a) presents the comparison for the fully loaded FPSO in a collinear environment, while Table 2(b) is for a crossed environment with the wind at 15 degrees to the waves and current. The model test 3-hour maxima are based on an estimate from nine hours of model test data. In both cases the dynamics of the thruster-assist system were fully modeled. Figure 6 presents a comparison between the calculated vessel RAOs and those obtained from the model tests for the vessel in head seas. The model tests also showed that the vessel was well designed to prevent greenwater on deck.

The excellent agreement between the model test and numerical simulations results indicate the accuracy obtained in modeling the Terra Nova FPSO response. The numerical simulations were then used to develop design load cases for the design of the turret structural and mechanical components, and the turret-vessel interface. Figure 7 presents the stress and deflection variation in the turret-vessel structure in a 100-year storm, accounting for the bending of the hull and the mooring load transfer through the turret system. This sophisticated analysis is required due to the requirements of obtaining the maximum deflection for the turret bearing system, and the stress variation around the moonpool of the vessel.

Pack Ice Loads. The pack ice loads on the vessel and mooring were estimated from the model tests. The model ice was developed to have the correct scaled structural properties of first year pack ice. Figure 8 summarizes the total maximum load on the turret mooring as a function of surface coverage percentage, for ice floes with a thickness of 1 meter. The load is expressed as a percentage of the maximum design mooring load in the 100-year storm environment.

The figure shows that even at 100% coverage the loads are less than 75% of the maximum mooring load. Pack ice coverage at the Terra Nova site is not expected to be more than 60% implying that pack ice loads on the FPSO are well within the design parameters of the mooring system.

Spider Buoy Disconnect Analysis. The transient response of the spider buoy disconnection was analyzed in detail using a time-domain model of the spider buoy, the mooring and the risers. Several simulations were run in the maximum disconnect seastates with the buoy being disconnected at various positions in the waves. This was done to ensure that the spider buoy would drop away quickly from the vessel without contacting with the vessel keel, to determine the maximum dive depth, and to study the riser interaction with the seabed. Figure 10 shows a comparison of the spider buoy free fall from the numerical simulation with the result obtained from a model test, once again showing a good comparison.

Summary and Conclusions

The paper outlines the methodology used to perform the global analysis and design of the Terra Nova FPSO turret mooring system. The paper illustrates the integrated engineering effort between the vessel, mooring and riser designers to develop an optimum FPSO system, given the design basis prescribed.

The paper also illustrates the FPSO global analysis methodology and its integration with a comprehensive model test program, resulting in the development of an optimized turret mooring design. This resulted in the development of a turret mooring system that met the challenging requirements for disconnect and reconnect operations, and 100-year storm survival criteria.

Acknowledgment

The authors would like to thank the Terra Nova Alliance for granting them permission to publish this paper. The authors would also like to thank the many engineers from FMC SOFEC, Shawmont Brown and Root, and Coflexip Stena Offshore who have worked to optimize the global design of the FPSO turret mooring system, and have provided detailed information on the various subsystems.

References

1. Lloyd’s Register, Rules and Regulations for the Classification of Ships, January 1997.
2. Lloyd’s Register, Rules and Regulations for the Classification of Fixed Offshore Regulations, December 1989.
3. Doyle, T. and Leitch, J.: “Terra Nova Vessel Design and Construction,” Offshore Technology Conference, OTC 11920, May 2000.
4. Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures, API RP 2SK, Second Edition, December 1996.

Table 1 – Design Environmental Criteria at Terra Nova.

Parameter	Return Period (Years)		Units
	1	100	
Wind Velocity			
1-hour mean wind speed	28.8	39.6	m/s
Wave Parameters			
Spectrum Model	JONSWAP	JONSWAP	meters
Significant Wave Height	10.9	16.0	meters
Peak Period Range	12.9 - 16.6	15.7 - 20.2	seconds
Peakedness Parameter, γ	1.0 - 1.7	1.0 - 1.7	
Maximum wave height	20.7	30.4	meters
Associated period range	11.5 - 17.6	14.1 - 21.3	seconds
Current Velocity			
Near surface (20 m)	1.00	1.30	m/s
Mid depth (45 m)	0.86	1.09	m/s

Table 2 – Comparison of Results from Numerical Simulations and Model Tests: (a) 100-year Collinear Environment, (b) 100-year Crossed Environment

Collinear 100-Year Environment

			Model Test	Prediction
Horizontal Offset	Mean	m	-7.0	-6.8
@ Turret	Maximum	m	-20.6	-20.8
Turret Loads	FXY (mean)	MT	407	348
	FXY (max.)	MT	1804	1897
	FZ (mean)	MT	-935	-1054
	FZ (max.)	MT	-1764	-1825
Anchor Leg Tension	Mean	MT	226	222
	Maximum	MT	640	688
Vessel Wave Frequency	Pitch (max.)	deg	7.0	7.1
Motions @ Turret	Z Turret (max.)	m	10.9	10.6
Accelerations @ Swivel	X acc. Swivel (max.)	m/s^2	1.2	1.3
	Z acc. Swivel (max.)	m/s^2	2.2	2.0

Crossed 100-Year Environment

			Model Test	Prediction
Horizontal Offset	Mean	m	-8.7	-8.9
@ Turret	Maximum	m	-20.0	-20.9
Turret Loads	FXY (mean)	MT	491	426
	FXY (max.)	MT	1662	1783
	FZ (mean)	MT	-959	-1102
	FZ (max.)	MT	-1814	-1786
Anchor Leg Tension	Mean	MT	225	244
	Maximum	MT	584	593
Vessel Wave Frequency	Pitch (max.)	deg	7.0	7.1
Motions @ Turret	Z Turret (max.)	m	10.9	10.6
Accelerations @ Swivel	X acc. Swivel (max.)	m/s^2	1.2	1.3
	Z acc. Swivel (max.)	m/s^2	2.2	2.0

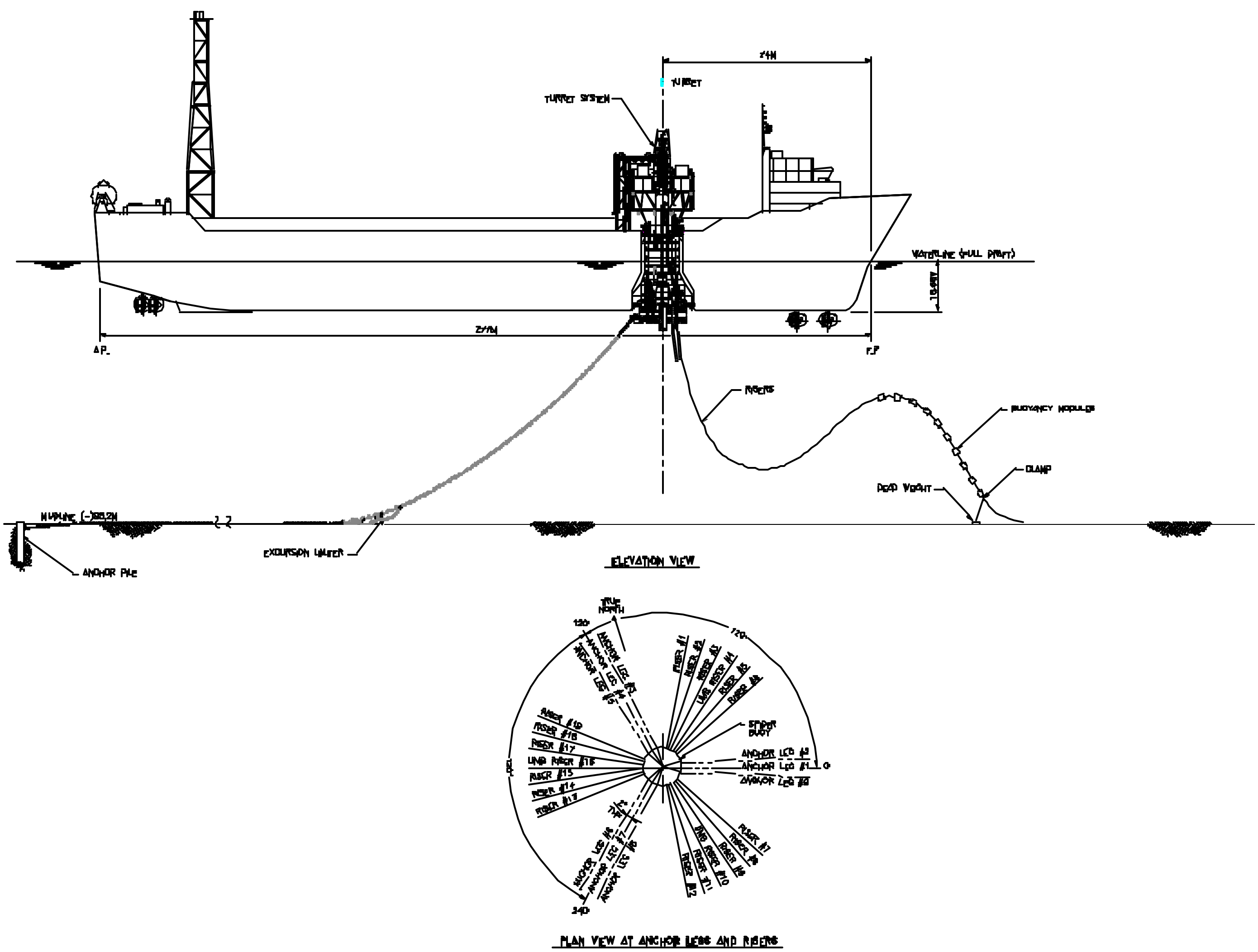


Figure 1 – General Arrangement of the Terra Nova FPSO and Turret Mooring System

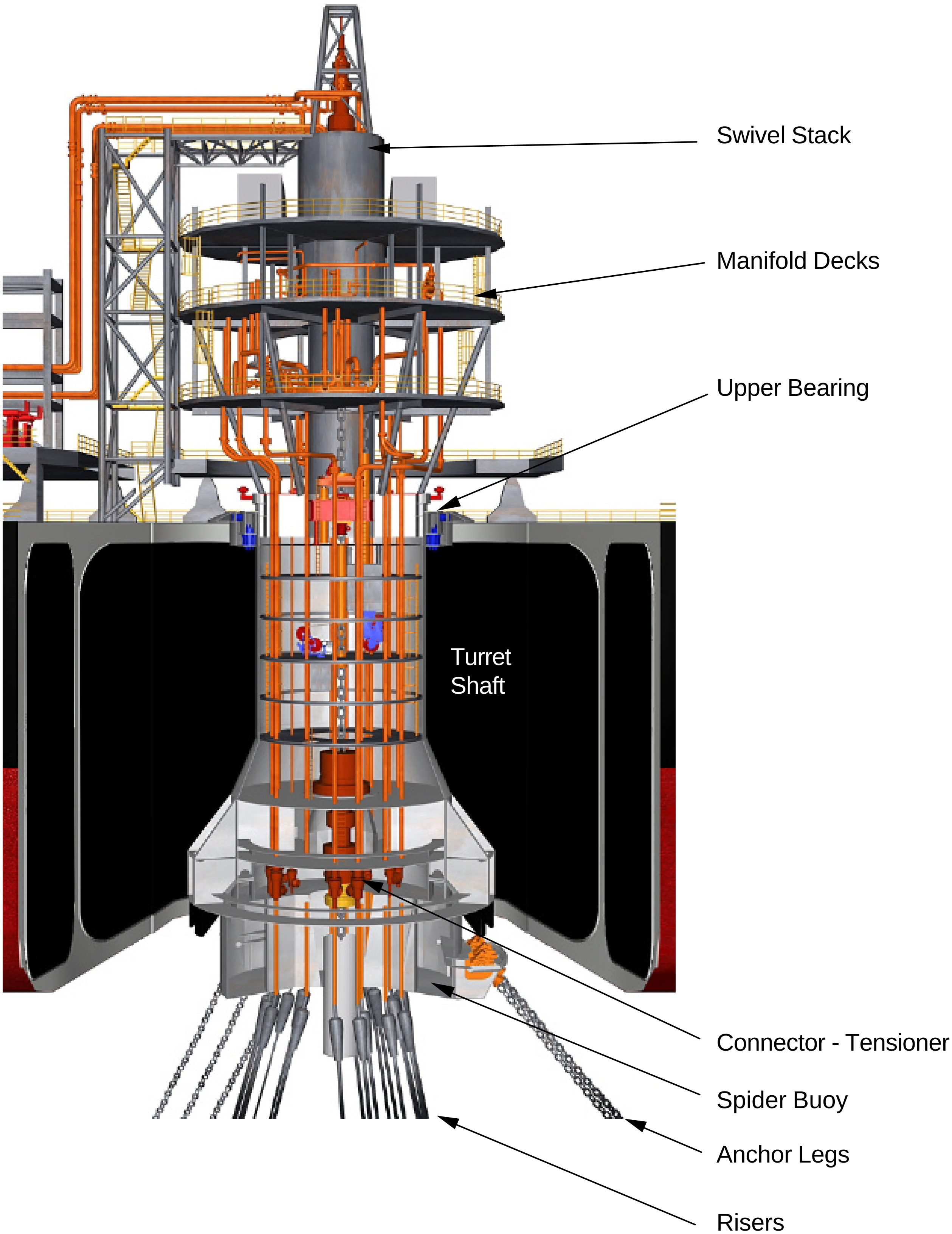


Figure 2 – Schematic of Turret Mooring System

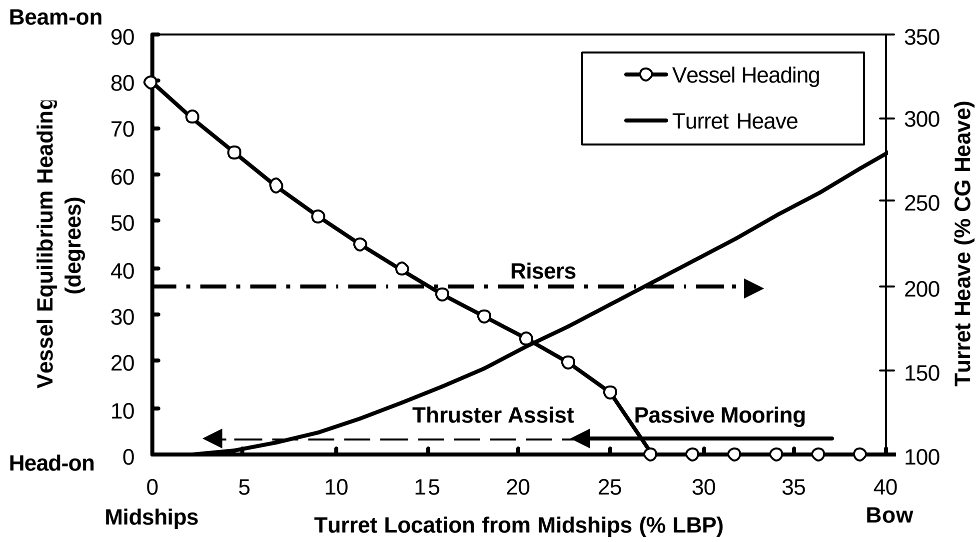


Figure 3 – Impact of Turret Location on Vessel Equilibrium Heading

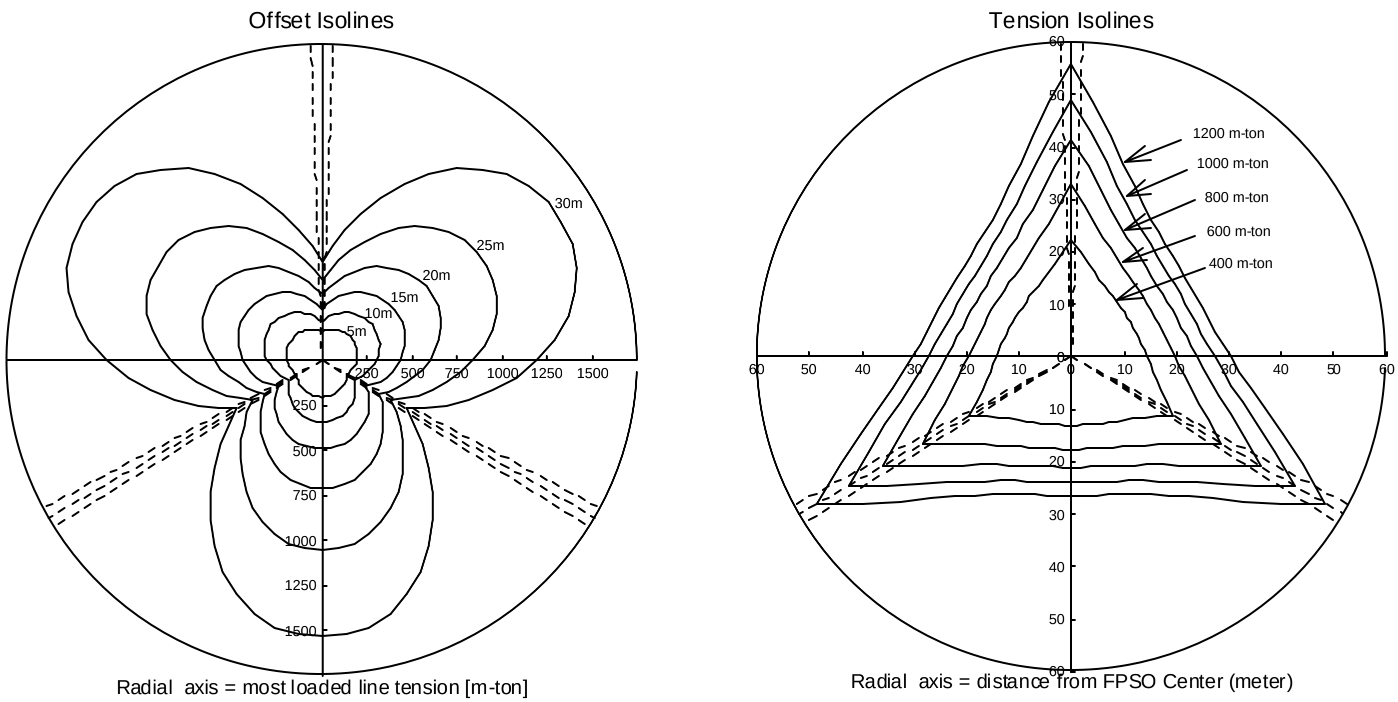


Figure 4 – Offset and Most Loaded Line Tension Isolines as a function of Mooring Orientation

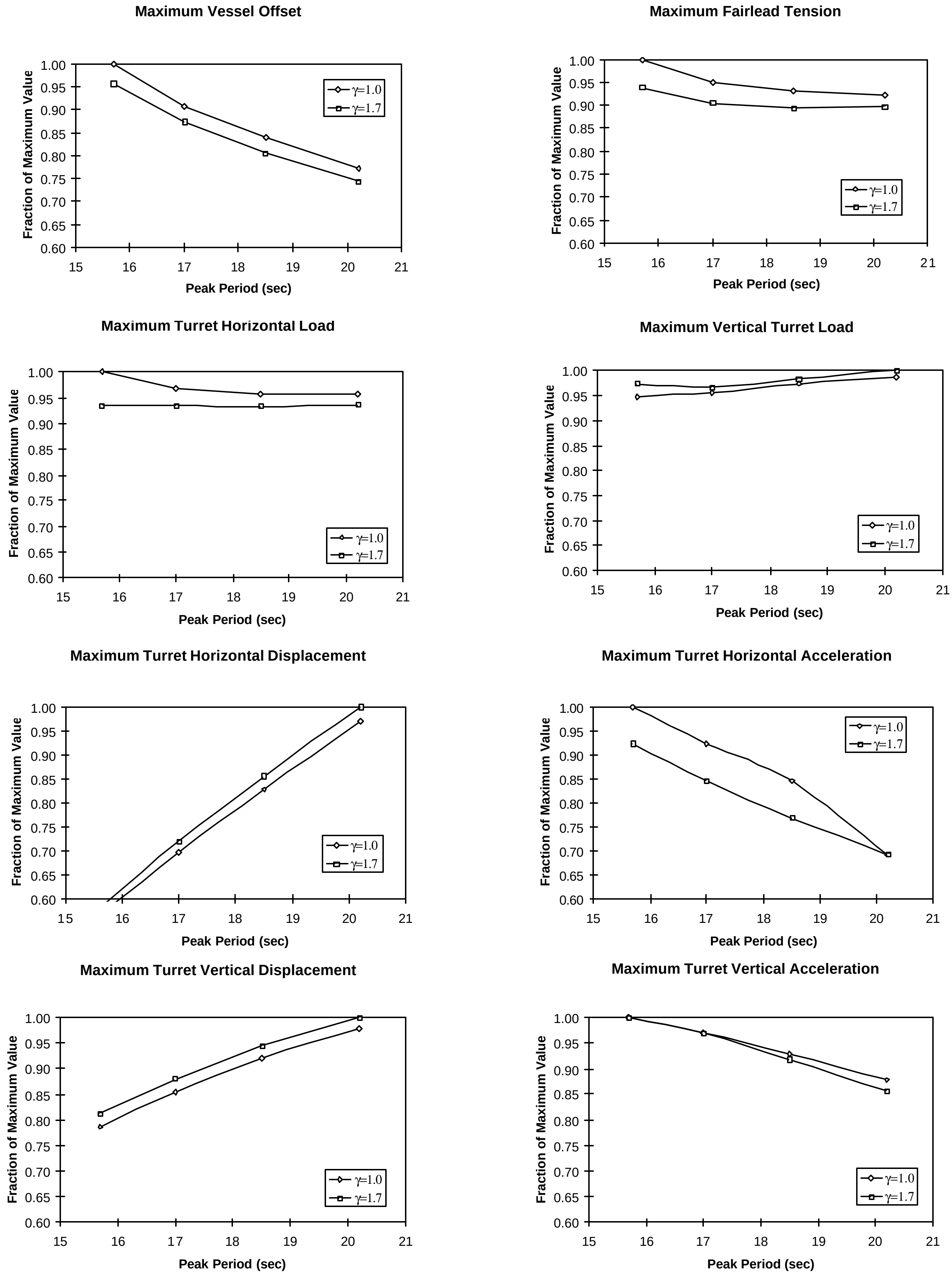


Figure 5 – Sensitivity of FPSO Response as a function of Wave Spectral Period and Peakedness Parameter

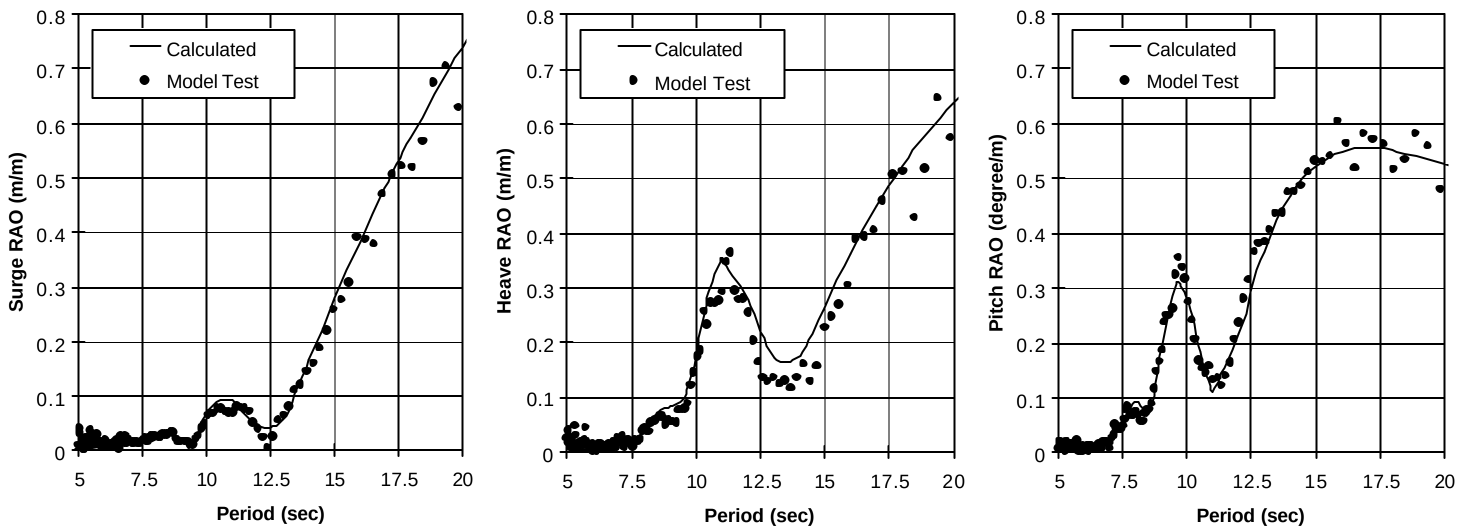


Figure 6 – Comparison of Computed and Measured Vessel RAOs for Head Seas

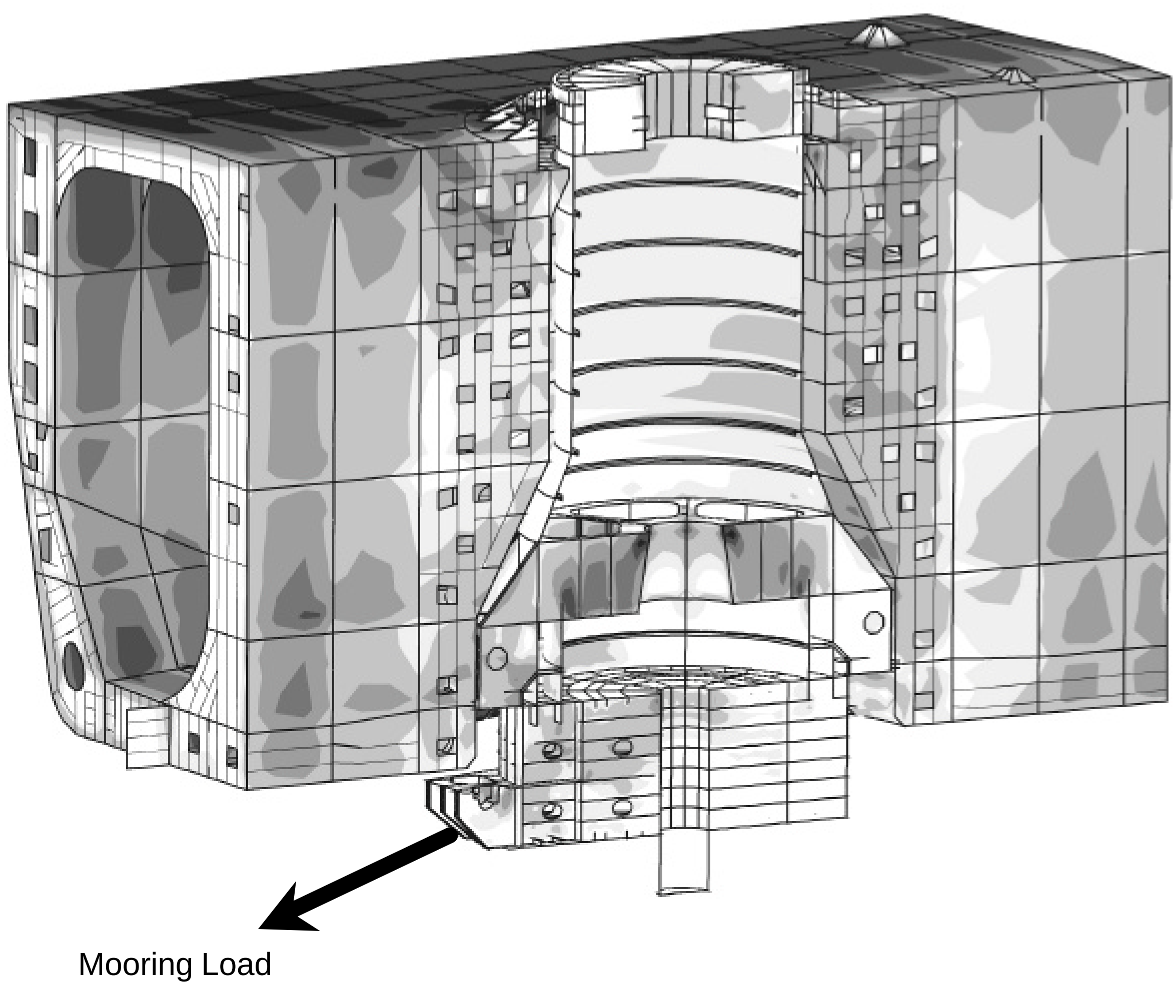


Figure 7 – Stresses and Deflections from Finite Element Model of Turret and FPSO Vessel in 100-year Storm Environment

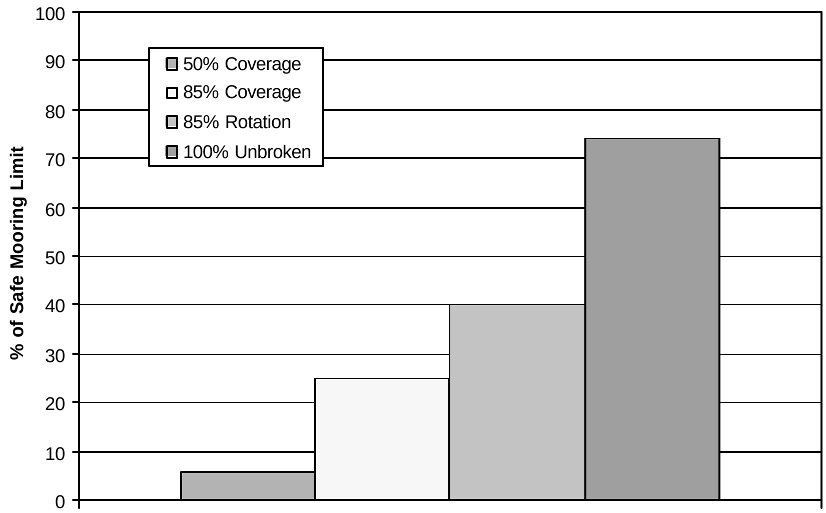
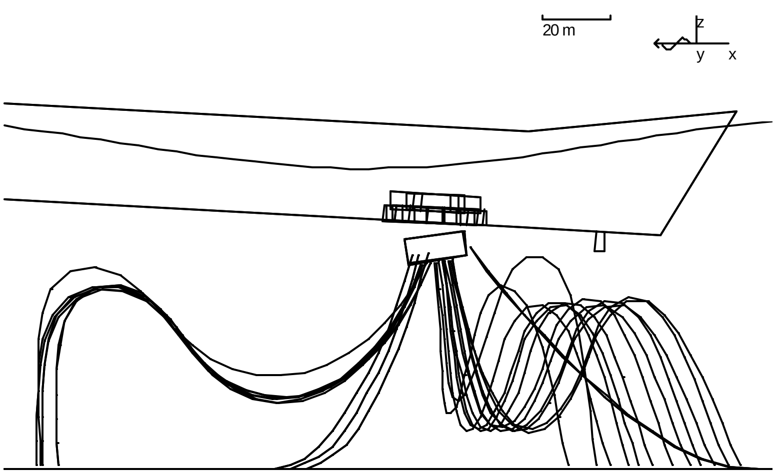


Figure 8 – Pack Ice Loads on FPSO as a function of Surface Coverage



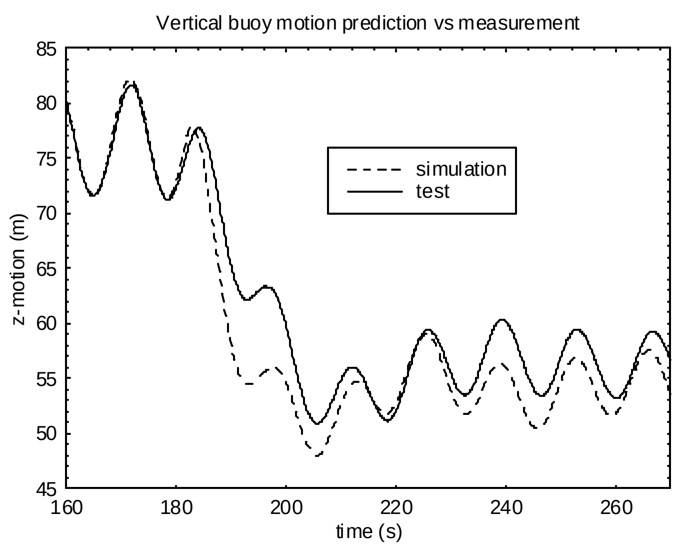


Figure 9 – Comparison of Computed and Measured Free Fall of Spider Buoy in Maximum Disconnect Environment