Terra Nova FPSO: Integration of Model Tests and Global Analysis

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ABSTRACT

The Terra Nova FPSO is located on the Grand Banks, offshore Eastern Newfoundland, Canada, in 95 meters of water. The FPSO has been designed with an internal turret mooring system that must withstand the harsh 100-year storm environment, and be disconnectable to avoid collision with large icebergs.

The paper focuses on the integration of a comprehensive model test program with the sophisticated analytical and numerical global analysis performed on the FPSO system. The paper illustrates the importance of the model test program as a tool in the conceptual design, verification of the global analysis, and detailed engineering and installation of the system. In addition, the model test program provided the opportunity to study what-if scenarios, and was an effective instrument in obtaining certifying and regulatory authority approval. As the Terra Nova FPSO is the first floating production system to operate in an iceberg region, a major focus of the model test program was to study the interaction of pack ice and icebergs with the FPSO system.

Keywords: FPSO, Model Test, Global Analysis, Terra Nova

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. First oil is expected in the first quarter of 2001. 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, supporting 14 risers and 5 umbilicals. The internal turret mooring system has been designed to maintain on station in the 100-year storm environment, and to be disconnectable only 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, and the detailed design of its mooring system, requires knowledge of the interaction of the environment, vessel and mooring system. The analysis of the Terra Nova system is further complicated due to the use of an automatically controlled thruster system to assist the mooring, the analysis of the dynamics of the disconnect and reconnect operations, and the requirement to design for pack ice and iceberg loads.

The Terra Nova project is a fast track development with an ambitious schedule of concept development to first oil in less than 4 years. The model test program for the Terra Nova FPSO was developed to maximize the synergy of the global analysis with key milestones of the master project schedule. Due to the fast-track nature of the project the model test program was also used to provide an independent verification of the analysis performed on various system components, allowing long-lead items to be contracted early in the project.

Model testing played a very important role in the development from conceptual design through detailed engineering, to fabrication and installation. This is true even though state-of-the-art numerical simulation techniques provide fairly accurate estimates of the system response in most cases. In most cases numerical and analytical analysis were used to develop the design loads for the system with the model test data providing verification. The model tests were also used to provide empirical data for design, study what-if scenarios, and provide an insight into the complex interactions between the various systems that may not have been evident from the numerical analysis alone. The video record of the model tests was used with great success in providing feedback to system designers and in obtaining client, certifying and regulatory authority approval for system design.

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.

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	
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 1 – Design Environmental Criteria at Terra Nova

Description of the Terra Nova FPSO System

The new build, ice-strengthened vessel has been 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 a displacement of 193,000 MT and a mean draft of 18.6 meters. The vessel freeboard has been designed to minimize greenwater on the main deck. The vessel has five azimuthing thrusters (5 MW) each that 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 Doyle and Leitch (2000).

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 location of the turret 74 meters aft of the forward perpendicular requires the use of thruster assistance to provide heading control. 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 14 risers and 5 umbilicals are arranged in between the anchor leg groups, using a pliant wave configuration. When released the spider buoy settles at an equilibrium depth of 35 meters, supporting the anchor legs and the risers and umbilicals. Figure 1 provides a general arrangement of the FPSO vessel and mooring system. Additional details on the turret mooring system are provided in Duggal, Heyl and Vance (2000).

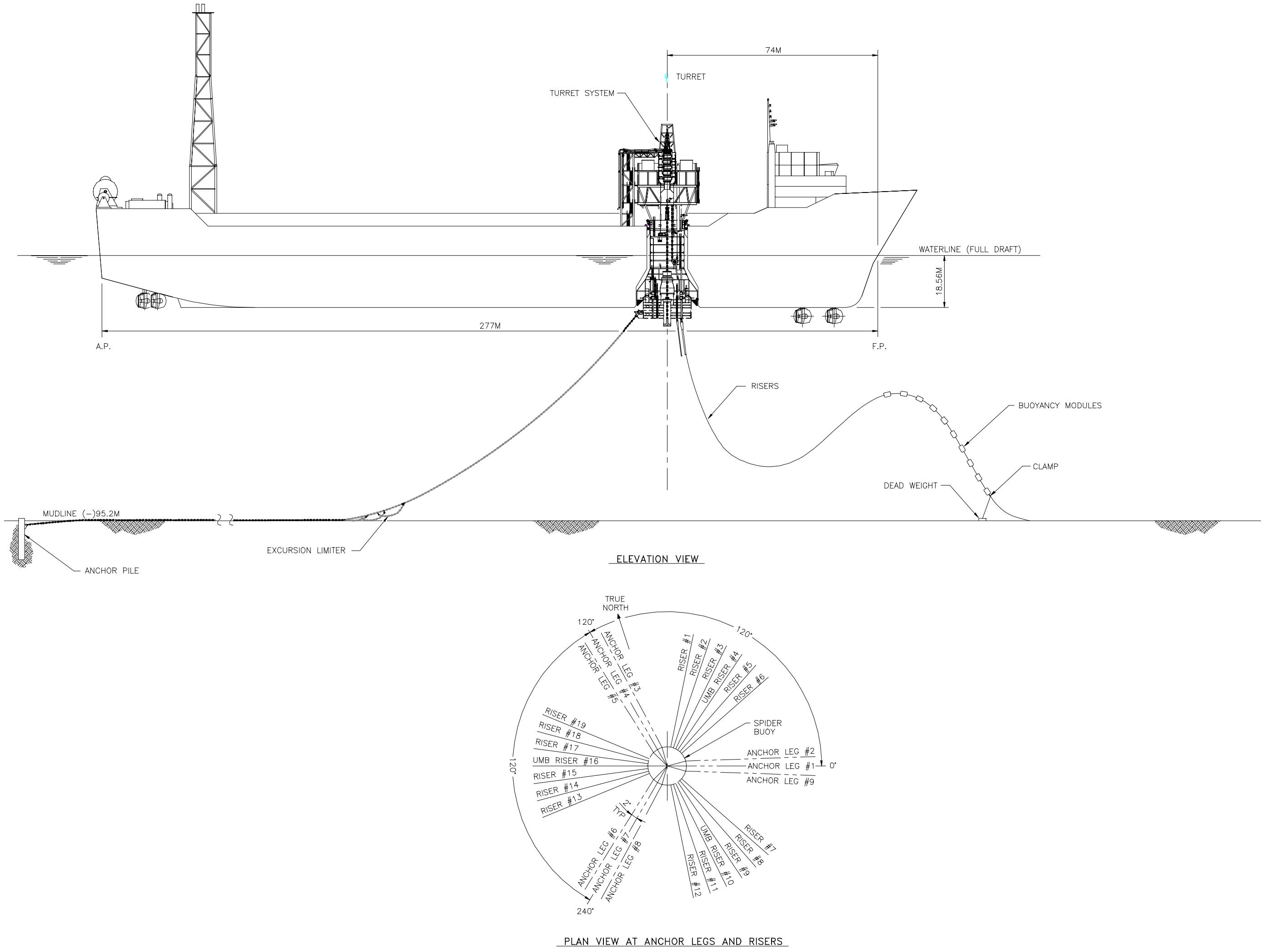

Figure 1. General Arrangement of the Terra Nova FPSO and Turret Mooring System.

Analytical and Numerical Modeling

The harsh environment, shallow water depth, and the non-linear nature of the Terra Nova FPSO mooring system, result in a challenging 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.

The numerical simulation of the FPSO vessel and mooring system used both frequency-domain and time-domain models to study 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 (1996).

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 various design load conditions. The frequency-domain model 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 system after disconnect, and the steady-state response of the system after the buoy reaches its equilibrium depth. This provided information for the design of the riser system, including interaction with the seabed and 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 was conducted at several different test facilities over a period of about one year. The model tests ranged in complexity from traditional resistance and propulsion tests to tests with the complete FPSO system comprised of the vessel with automatic controlled thruster system, turret system with disconnectable spider buoy and retrieval equipment, and all anchor legs and risers, with 100+ channels of data being recorded.

A well designed model test program requires a detailed knowledge of the system to ensure that all hydrodynamic, structural and mechanical properties are modeled accurately. The global analysis should have proceeded to an advanced stage to provide input into the selection of environmental conditions and system conditions to optimize the model test program. Careful attention should be paid to the fabrication of model components, selection and calibration of the instrumentation, and installation of the model. Finally the model system should be accurately tested and calibrated to ensure that the system is representative of the actual system being tested and meets the objectives of the test program. For example, the Terra Nova survival environment test program had a total duration of three weeks, with two weeks spent in model set-up and calibration, and one week for the actual testing.

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 resulting coefficients were used as input in the global analysis of the system, and will also be utilized by the automatic control system on the FPSO for the wind feed-forward mode. In addition, tests were conducted to estimate the velocity distribution around the helideck, flow visualization of the wind field around the vessel, and smoke tests to validate the funnel design. These tests were conducted at the Danish Maritime Institute.

Resistance and Propulsion Tests. These tests were conducted with a model of the hull at a scale of 1:27 to study the free-sailing characteristics and maneuverability of the new build hull. The tests provided information on the calm water resistance of the hull, and self-propulsion and added power in irregular waves. This information was used to plan the delivery voyage from Korea to Newfoundland, and the maneuverability of the vessel after disconnect. The tests were conducted at the Institute for Marine Dynamics (IMD), Newfoundland.

Vessel Response Tests. These tests focused on providing data on the vessel response and greenwater on deck as a function of relative wave heading. The vessel was held in a horizontal mooring system that was designed to minimize its influence on the vessel wave-frequency motions. The tests also provided estimates of the mean wave drift force and moment on the vessel. Relative wave and greenwater probes, and video cameras were mounted on the exposed side of the vessel to monitor the wave-vessel interaction and passage of greenwater on the deck. 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 greenwater. The tests were also used to study the effectiveness of bilge keels in reducing the roll response. The tests were conducted at Marintek, Norway and IMD.

Survival Environment Tests. The tests served as the primary verification of the FPSO system response and performance, for a selected set of design environmental conditions (1-year and 100-year storms). The wave basin tests were carefully designed to ensure that only environmental conditions that could be accurately simulated in the basin were used, resulting in a high quality dataset for comparison to the numerical simulations. Once the simulation accuracy was verified, the numerical simulations were used to perform the detailed system analysis and in the development of the design loads for the system.

The thruster system was also modeled and controlled by a control system similar to the prototype. The system was tuned by evaluating the step response of the system for surge, sway and yaw and adjusting the "gains" in the control system to provide the desired response. The thruster-assistance performance was evaluated as a function of various modes of operation from heading control only, to full thruster assist with surge damping, to the "blackout" condition with no thruster-assist. Various setting in the system were also studied to provide input for the operability of the system. The tests were conducted at Marintek (scale 1:60) and IMD (1:44).

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. All the risers were modeled and their response monitored with loadcells and video, especially during disconnect and in the disconnected mode. 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 detailed numerical simulations. The tests were conducted at IMD.

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 model ice was designed to have the correct scaled mechanical properties of pack ice. 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 study the interaction between the pack ice and the vessel, and the total loads on the mooring system. These tests were also used to determine the disconnect limit for pack ice coverage.

Iceberg and Bergy-Bit Impact Tests. A series of tests were conducted to study the impact of a 100,000 MT iceberg, and a 3,500 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 iceberg tests were conducted in current only while the bergy bit tests were conducted in current and 1-year storm waves. The iceberg and bergy-bit models had a "bumper" made of floral foam that was shown to have scaled mechanical properties similar to that of iceberg ice. The bergy-bit and iceberg models had self-contained instrumentation and data storage packs that recorded the impact load and accelerations. A number of tests were conducted to provide estimates of impact loads as a function of impact velocity, angle of approach, and repeatability. These tests were carried out in conjunction with the survival tests at IMD.

Installation Tests. The model tests were also used to optimize the installation of the spider buoy and the mooring system. An experimental program was developed to study spider buoy stability under tow and during installation. This allowed the project to optimize the vessels and equipment used during the installation, with a positive impact on installation schedule and cost.

Results from the Model Test Program

Due to space limitations, only a few examples of the results obtained from the various stages of the model testing program and global analysis are presented.

The wind tunnels tests were conducted early in the program to provide an accurate estimate of wind and current loads on the vessel. The wind loads were estimated using a semi-empirical numerical model before the wind tunnel tests were conducted. Figure 2 compares the longitudinal and transverse wind coefficients as a function of vessel heading from the wind tunnels tests and the numerical model. The figures show that the longitudinal force estimates compare well while the numerical model underestimates the transverse force. The transverse wind load is important as it impacts the sway-yaw response of the system and the thruster forces required to maintain heading. The wind tunnel coefficients were used as input in the final global analysis of the system and in the actual vessel thruster control system.

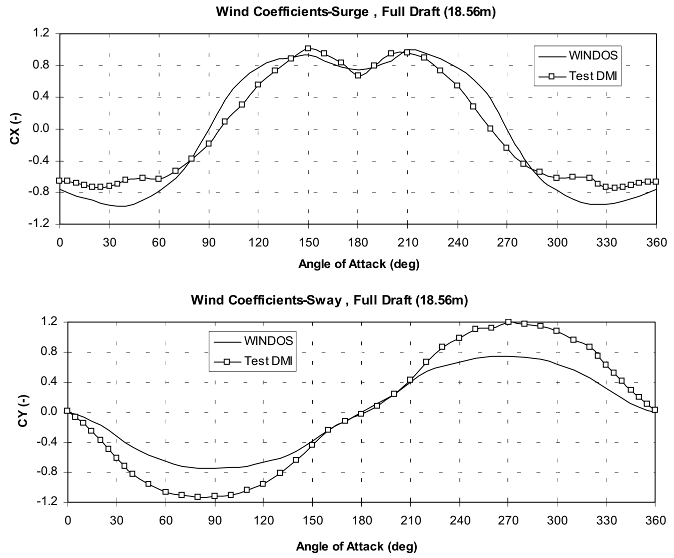

Figure 2 – Comparison of Wind Coefficients from Wind Tunnels Tests and Numerical Simulation.

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, where the individual 3-hour maxima were found to vary by ~15%, typical of a shallow water system with low damping. In both cases the dynamics of the thruster-assist system were fully modeled. Figure 3 presents a comparison between the calculated vessel RAOs and those obtained from the model tests for the vessel in head seas.

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

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

The excellent agreement between the model test and numerical simulation results indicates 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.

The transient response of the spider buoy disconnection was analyzed in detail using both model tests and numerical simulation. The primary objectives were to ensure that the spider buoy would drop away quickly from the vessel without contacting with the vessel keel, determine the maximum dive depth, and study the riser interaction with the seabed. Figure 4 shows a comparison of the spider buoy free fall from the numerical simulation with the result obtained from a model test, showing excellent agreement.

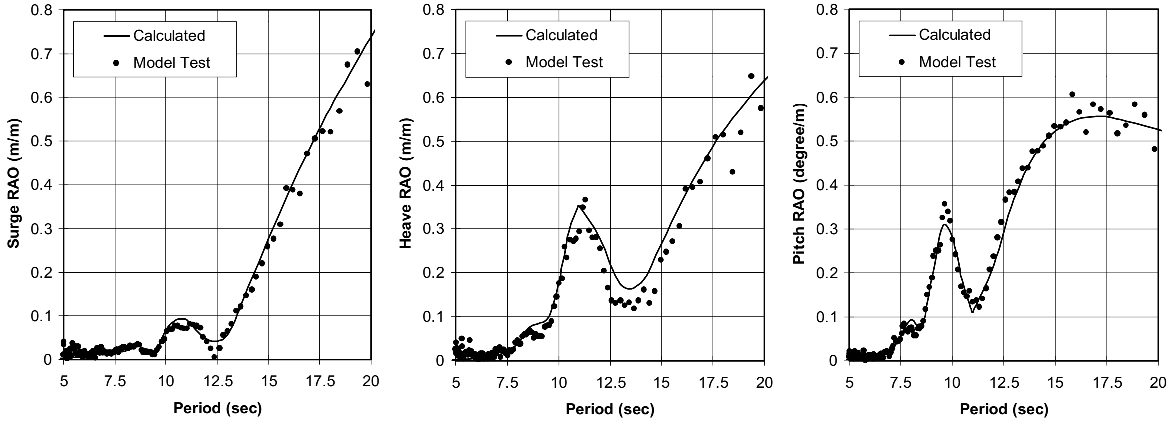

Figure 3. Comparison of Computed and Measured Vessel RAOs for Head Seas.

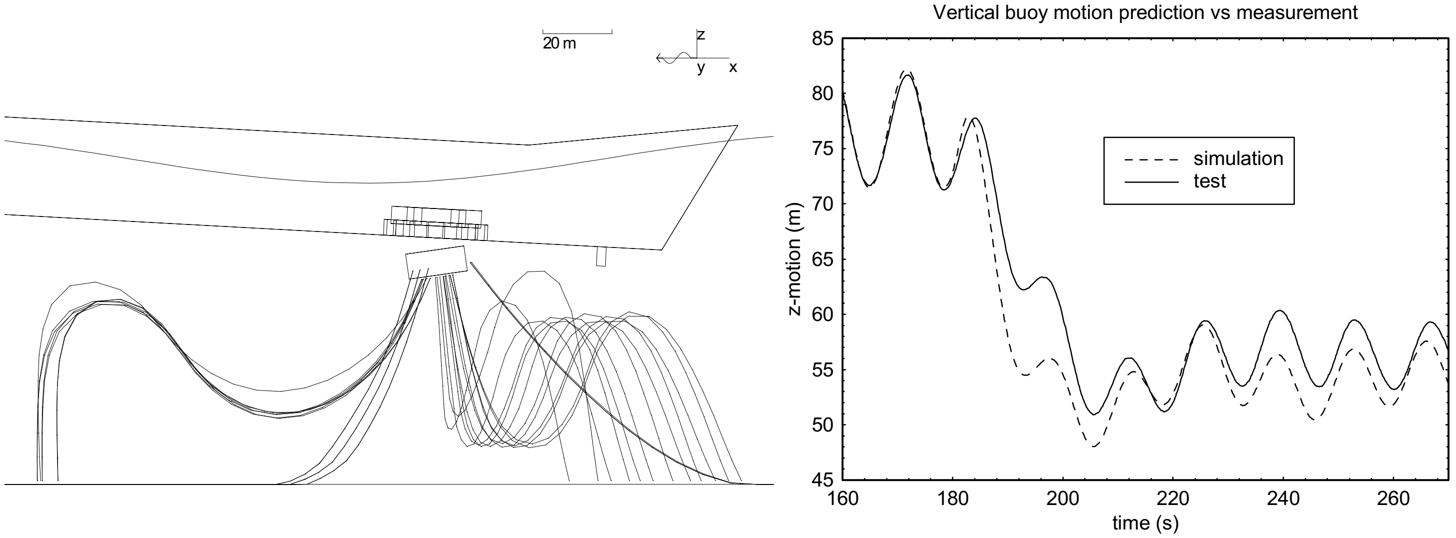

Figure 4. Comparison of Computed and Measured Free Fall of Spider Buoy.

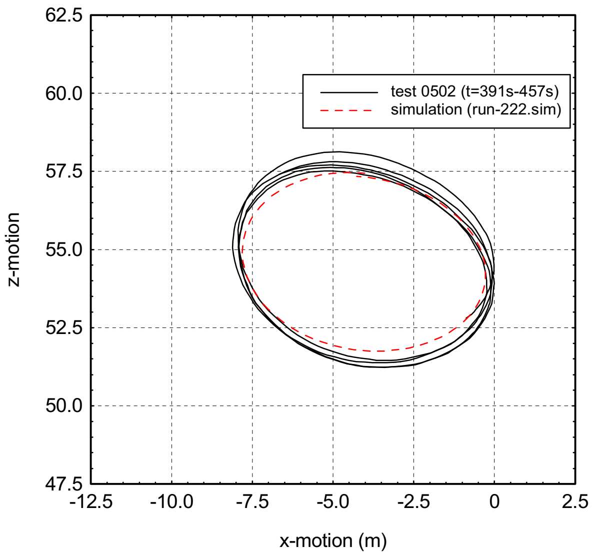

Figure 5. Spider Buoy Motions in Regular Waves.

The disconnected spider buoy response was studied using both regular and random waves. Of interest were the motions of the buoy and the response of the riser system. Figure 5 presents a comparison between model test and simulation of the motion of the buoy in the XZ plane when subject to regular waves. The comparison shows excellent agreement between the two models indicating that the drag and inertia coefficients selected for the buoy and riser system accurately represent the wave load on the system. The numerical model was then used extensively by the riser manufacturer to design the riser system.

The retrieval of the buoy and the associated dynamics was also studied in detail. The model tests were conducted with an instrumented winch that retrieved the buoy at the design speed, while the vessel maintained its position over FPSO center using the automatic control dynamic positioning system. The retrieval load time history is characterized by "snap" loading at the initial stages of the retrieval and a steadily increasing load as the buoy nears the turret. The snap loading is caused by the difference in phase between the buoy and the vessel when the buoy is near its equilibrium position. When the vessel pitches up it pulls the buoy up; however, when the vessel pitches down the descent of the buoy lags that of the vessel, causing the chain to go slack. On the next cycle when the vessel pitches up again the buoy is still descending, causing a snap load in the chain. Figures 6(a) and 6(b) compare the snap loading measured in regular waves to that predicted by the numerical model respectively. The comparison between the two is excellent demonstrating that the numerical model captures the dynamics between the vessel, buoy and the chain. The numerical model was then used to assist in the design of passive shock absorber to minimize the snap loading in the chain.

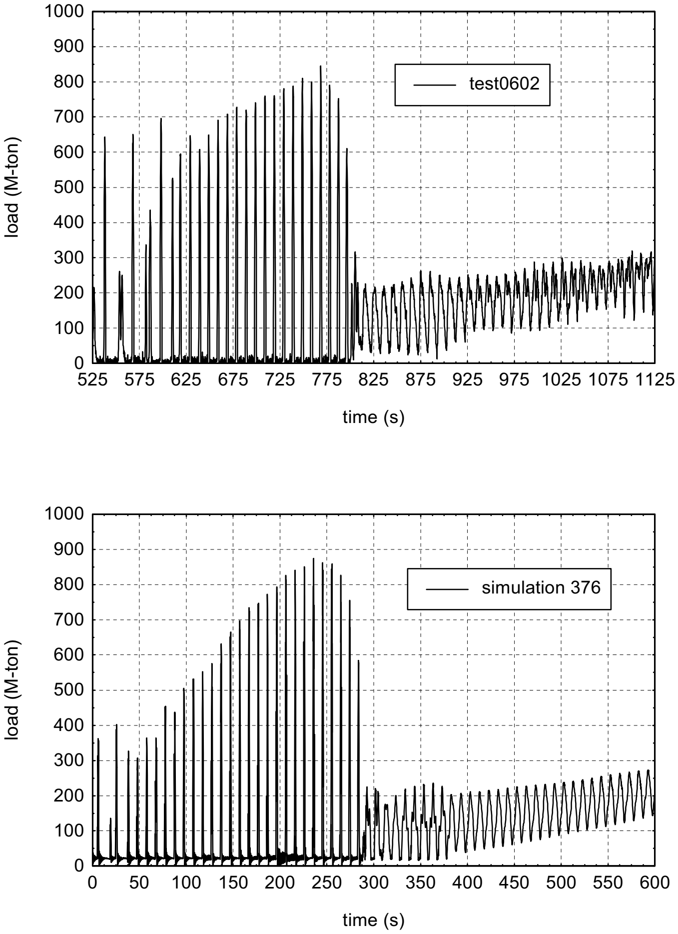

Figure 6. Snap loading in Retrieval Chain (a) model test (b) simulation.

The pack ice loading on the vessel and model tests was estimated using model test data. Figure 7 presents two curves derived from the data for 1 meter thick pack ice at 50% coverage; the mean pack ice load and an estimate of the 24-hour peak pack ice load. As expected the load increases as velocity increases. In general, the pack ice loads on the FPSO are well below the maximum system design loads.

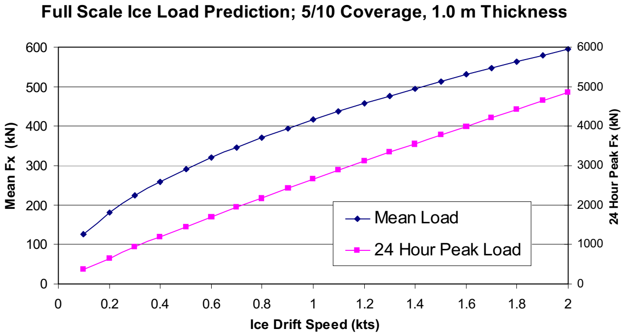

Figure 7. Pack Ice Load on FPSO in 5/10 Coverage.

A series of tests were also conducted to study the interaction of icebergs and bergy-bits with the FPSO system. Figure 8 presents curves extracted from the data showing iceberg and bergy-bit impact force as a function of impact velocity. As expected the iceberg impact load increases with an increase in impact velocity; however, the bergy-bit impact loads decrease with increase in impact velocity. This is a surprising result at first but can be explained by the fact that the waves reflect off the vessel resulting in a "cushioning" of the impact. A detailed study of the video recording of the interaction provided the same conclusion. Additional details on the ice loads on the Terra Nova FPSO can be found in Colbourne (2000).

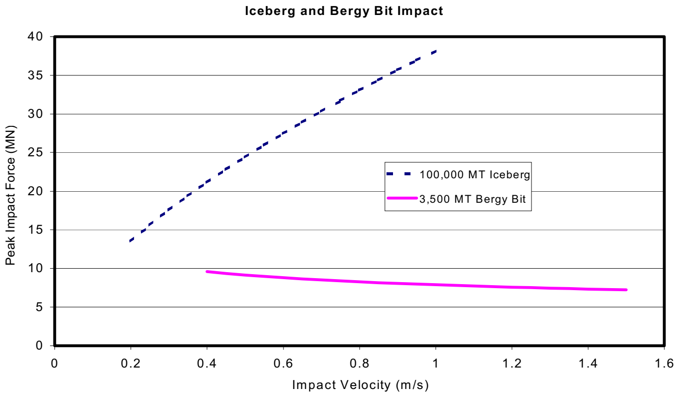

Figure 8. Iceberg and Bergy-Bit Impact Loads on FPSO.

Summary and Conclusions

The paper illustrates the importance of integrating the model test program with the global analysis of the Terra Nova FPSO. The model test program was used to provide an independent verification of the FPSO system response for all facets of the global analysis. The model tests were also used to provide empirical data for wind, current, pack ice and iceberg impact loads, and input in determining operational limits. The paper presents comparisons between the model test results and those obtained from the numerical analysis, which illustrate the accuracy of the numerical analysis performed.

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