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DP FPSO – A Fully Dynamically Positioned FPSO for Ultra Deep Waters

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ABSTRACT

In the coming years, there will be a growing demand for Floating Production and Storage Units (FPSOs) for ultra deep waters (greater than 2,000 meters) worldwide. One of the issues in the design of FPSOs for these water depths will be the selection of the most cost-efficient station keeping system for the specified operational requirements. Standard solutions based on internal turret mooring systems are already being offered by the industry. However, beyond certain water depths, the technical and economical constraints associated with the use of mooring systems may favor other concepts potentially more attractive and cost-efficient, such as a fully dynamically positioned FPSO. This paper presents the preliminary results from a design study being undertaken by the authors and their respective organizations to develop such a system. The paper provides a description of the FPSO hull and station keeping system and the disconnectable turret-riser system developed specifically for this application. Finally the paper compares results obtained from a comprehensive large-scale model test program of the system with numerical simulations.

KEY WORDS: FPSO; Dynamic Positioning; Ultra Deep Water; Model Tests; Global Analysis

INTRODUCTION

There is a growing demand for cost-effective and reliable floating production system concepts for ultra-deep water depths (greater than 2,000 meters). Floating, Production, Storage and Offloading (FPSO) systems are a mature floating production technology that is readily adaptable to deep water and is one of the floating production system of choice offshore Brazil and West Africa. Though there are currently no FPSOs in the deepwater Gulf of Mexico (GOM), the technical and economical limitations inherent to other type of concepts, the lack of pipeline infrastructure in ultra deep water, and the wide acceptance of the FPSO concept by Shelf Authorities should result in these systems being considered to be deployed in the near future.

One of the critical issues in the design of FPSOs for ultra deep waters is the design of the most cost-efficient station keeping system for the specified operational requirements. The capital cost of the station-keeping system including its installation can increase dramatically with an increase in water depth. In addition, seafloor congestion, poor geotechnical conditions, or short field life may result in the traditional mooring system not being an optimum solution. Thus beyond certain water depths and for certain other conditions and applications, the technical and economical constraints associated with mooring systems may favor other concepts more attractive and cost-efficient, such as a fully dynamically positioned FPSO (DP FPSO). This concept combines state-of-the-art FPSO technology and latest generation drill ship technology for dynamic positioning and operation in ultra deep waters. This system can either be utilized as an early production system or as a full-fledged field development solution. The areas most suited for this application are the Gulf of Mexico, Brazil, West Africa and Eastern Canada.

An early comprehensive study of dynamic positioning of large ships in ultra deepwater was conducted for a large ocean mining vessel in 6,000 meters of water (Brink and Chung, 1981). The development of the DP FPSO builds from this and the experience obtained with the BP Seillian FPSO, and the latest generation of dynamically positioned drillships specifically designed for water depths up to 3,000 meters. The BP Seillian operated in the North Sea for 8 years as a dynamically positioned production platform and was recently re-deployed in deep water offshore Brazil as an early production system for the Roncador field in 1,853 meter water depth. In Brazil the Seillian has remained on station while offloading to standard and DP shuttle tankers without incident (Henriques, 2000; and Gardner, 1999). The latest generation deepwater drillships have been in operation almost 5 years in many deepwater regions worldwide and are designed to remain on station in seastates up to the 10-Year hurricane environment in the Gulf of Mexico. In addition many thruster-assisted turret-moored FPSOs are in operation in the North Sea and have been studied for the Gulf of Mexico (Wichers and van Dijk, 1999).

The paper describes a joint study undertaken by the various companies represented by the authors to develop a design for a fully dynamically positioned FPSO for ultra deep waters. The paper will address the technical issues associated with such a system by presenting the preliminary results from a rigorous engineering analysis, and the design effort undertaken by the partners for a DP FPSO on a hypothetical deepwater field in the Gulf of Mexico. The paper will focus on the design of the FPSO vessel and its stationkeeping system, and the disconnectable turret system to allow quick disconnect of the vessel from the riser system. Results from computer simulations and model tests of the system stationkeeping performance and quick disconnect from the riser system are also presented.

DESIGN BASIS AND ENVIRONMENTAL CRITERIA

The DP FPSO system has been developed and analyzed based on a design basis developed for a hypothetical deep water field in the Gulf of Mexico. The water depth selected was 2,500 meters, and the field was assumed to be produced from three drill centers. A total of twelve (12) risers and four (4) umbilicals were assumed to interface between the drill centers and the FPSO. The riser system consists of six (6) 12" pipe in pipe production risers, two (2) 10" water injection risers, one (1) 10" gas injection riser, one (1) 12" gas export riser, and two (2) additional 10" gas lift/injection risers. The production rate was assumed to be 125,000 barrels of oil per day, and the minimum storage capacity for the DP FPSO was set to be 1 million barrels of oil.

The DP FPSO system has been designed for the environmental conditions from the Gulf of Mexico. This allows the evaluation of the system stationkeeping performance in an extreme hurricane environment, and also in fairly mild operational conditions. This also covers a range of conditions anticipated in other regions of interest like offshore Brazil and West Africa. Results for other milder environments will be extrapolated by means of computer simulations.

The environmental conditions used for the design basis are derived from several sources and are considered to represent general conditions valid for the Gulf of Mexico. For this design effort it is assumed that the vessel is required to maintain station with risers attached for all extreme seastates including the 10-Year hurricane environment. For extreme seastates greater than this environment the vessel will disconnect from the riser system and sail away to avoid the storm. The DP FPSO may also disconnect from the riser system in order to evacuate the crew from the remote site if that is an operational preference.

The following table shows all combined environmental conditions that are considered in the current design basis document. In all conditions a NPD wind spectrum formulation is assumed. This data has been used for both the computer simulations and the model test program.

Table 1: Environmental conditions assumed for DP FPSO study

Sea State	Hs [m]	Tp [s]	γ [-]	μ_{waves} [deg]	Vw [m/s]	μ_{wind} [deg]	Vc [m/s]	μ_{CUR} [deg]
90% exc. Coll.	2.0	6.0	1.0	180	10.0	210	0.35	180
90% exc. Cross.	2.0	6.0	1.0	270	10.0	240	0.35	180
99% exc. Coll.	4.0	9.0	1.0	180	15.0	210	0.35	180
Loop current	3.8	9.0	1.0	270	15.0	240	2.13	180
10-Year WS	5.8	10.6	2.0	180	20.0	210	0.60	180
10-Year Hurr.	8.6	12.3	3.3	180	29.5	215	1.00	180
100-Year Hurr.	12.5	13.0	3.3	180	41.0	180	1.00	180

An assumption has to be made on the relative directions of waves, wind and current. The following situations are considered:

- Wind direction is always at an angle of 30° to the wave direction. The only exception is the 100-Year Hurricane condition, where wind and waves are considered to be parallel.
- Current is either in line (collinear) with the waves or perpendicular to the waves (crossed condition and loop current).

DESCRIPTION OF THE DP FPSO SYSTEM

The DP FPSO system consists of the hull and topsides, a thruster-based stationkeeping system, and a disconnectable riser turret that allows rapid disconnection from a large number of risers, when required. Figure 1 provides a schematic of the DP FPSO. The main components of the DP FPSO system are:

- **DP FPSO:** a 1,000,000 barrel storage vessel with production capacity for 125,000 barrels of oil per day. The FPSO has a DP-thruster stationkeeping system and offloads to a shuttle tanker connected in tandem.
- **Turret:** allows for transfer of fluids between the riser system and the vessel. The turret is designed to allow rapid disconnection from the riser system, providing the ability to sail away from a hurricane. This also provides the means of disconnecting from the riser system in case of a blackout or scheduled maintenance at a shipyard.
- **Riser System:** The riser system provides transfer of product from the wellheads to the FPSO, and is specifically designed for use in this concept with the disconnectable turret system developed.
- **Offloading Tanker:** for transporting the stabilized oil to onshore refineries. Currently conventional tankers with a capacity of approximately 500,000 barrels are considered in this study.

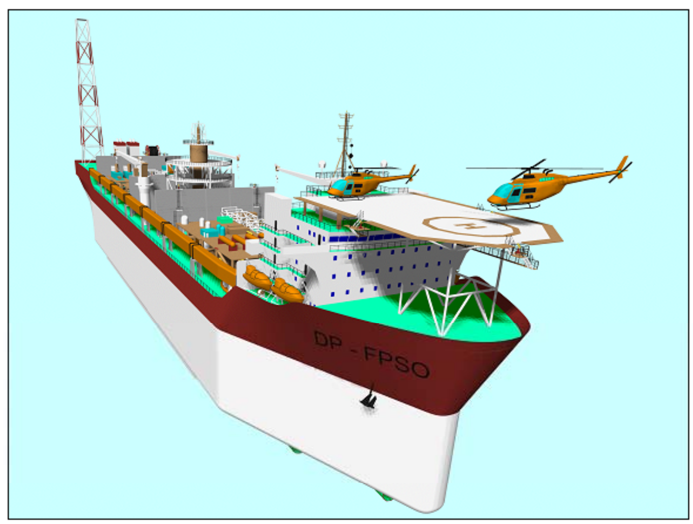

Figure 1. DP FPSO concept

FPSO Vessel Hull Design

The FPSO has been designed with a crude oil storage capacity of one million barrels, and is double sided and has a double bottom to comply in full with MARPOL regulations (International Convention for the Prevention of Pollution from Ships). The vessel hull forms are typical for a new-built FPSO, with a prismatic mid-body, a sloped flat transom and triangular bow. The turret is located amidships, to minimize the vessel motions affecting the riser system and the riser (dis)connection operations. A process plant weight of 15,000 tons is accounted for. Table 2 provides a summary of the main vessel particulars.

Cargo tanks are arranged forward and aft of the turret, as well as at both sides of the turret moonpool. Slop tanks are arranged aft of the cargo tank area. Ballast tanks are provided in the double hull, and fore and aft peaks. The power generation module is located on the aft main deck. Machinery spaces are located forward (underneath the accommodation block), and aft (under the power generation module).

The accommodation (and helideck) is located forward in order to provide adequate navigational capabilities, as it is envisaged that the FPSO will disconnect and sail away in extreme environmental conditions. The flare tower and the offloading equipment (hawser reel, hose reel, offloading station, etc.) are located at the stern.

Table 2. DP FPSO Particulars.

Parameter	Value	Units
Length (LBP)	260	meters
Beam	46	meters
Depth	28	meters
Storage	1,000,000	barrels
Topsides Weight	15,000	MT
Accomodations	100	p.o.b.
Offloading tanker	500,000	barrels

An enclosed gangway runs along one side of the vessel connecting the aft and forward vessel areas, with access from the main deck and process modules. This gangway is designed for safety of personnel in certain severe conditions, and to facilitate protecting piping and cabling. Blast walls are installed to provide a physical separation between the different areas and to avoid propagation of fire/explosion to adjacent areas in case of an accident. Transverse blast walls fore and aft of the turret, and a blast wall aft of the cargo tank area are also provided. Additionally, the aft accommodation bulkhead is designed to withstand the blast pressure and to protect the lifeboats. Cranes in adequate number and capacity will be spread throughout the deck to ensure proper handling of provisions, spares, equipment, etc.

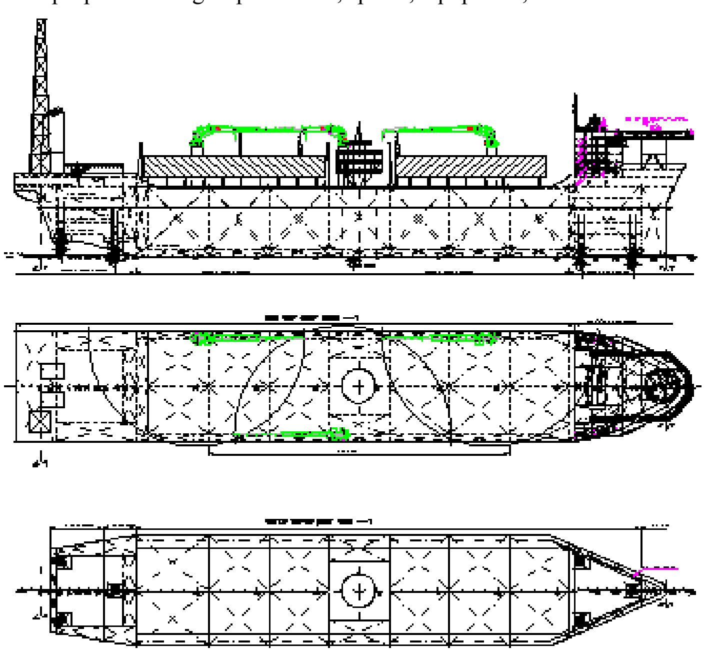

Figure 2. DP FPSO general arrangement

The DP FPSO is intended to operate permanently on site during the specified service life of 20 years without dry-docking. A high uptime of the installation is desired, similar to that of a conventional turret moored FPSO. For this purpose, the FPSO is provided with sufficient system robustness (redundancy of critical equipment, etc) to insure that operation can be made in a safe and efficient way for the conditions specified below. Adequate means for inspection and maintenance on site will be provided. Special attention will be paid to provide in-water maintenance capability for the thruster system.

FPSO Station-keeping System

The DP system is sized to provide the required stationkeeping performance governed by the riser system, in the extreme design environmental conditions. The maximum allowable riser system offset is approximately 10% of the water depth. The DP system is also sized to provide sufficient redundancy in case of thruster failure or its being out of service for maintenance.

The DP FPSO is provided with a DP system classified with DP AUTRO notation according DNV rules for ships Part 6 ch. 7, and is equivalent to IMO Class 3. This is an automatic position keeping system with redundancy in both technical design and physical arrangement. The main basic principle that is to be applied during the design of the DP FPSO is that a single failure shall not lead to a critical situation caused by loss of position or heading. For the DP FPSO a failure is defined as an occurrence in a component or system causing one or both of the following effects:

- Loss of component or system function
- Deterioration of functional capability to such an extent that the safety of the vessel, personnel or environment is significant reduced.

For the case of a DP FPSO, the definition of single failure has no exceptions and shall include incidents of fire and flooding, and all technical breakdowns of system and components, including all technical and mechanical parts.

The operational mode of the DP system is the Automatic Mode that involves automatic position and heading control, and is the selected mode when the unit is in operation. In addition, manual mode for each thruster is available. For periods where the unit is not in operation the provision of a Transit/Navigation Mode system is considered utilizing the aft port and starboard thruster for steering purpose and the remaining thruster in the zero position for propulsion.

The DP system consists of the following main subsystems:

- Thruster system
- Power generation system
- Control system
- Sensors

The Central Control Room is located within the accommodation block and is designated as the main control point of the unit. In the aft part of the FPSO an Engine Control Room is mounted adjacent to the engine room and is designated as the secondary control point of the vessel.

Thruster System: The thruster system comprises six (6) azimuthing fixed pitch, frequency controlled thrusters with an anticipated capacity of 5 MW each. The thrusters are located three (3) aft and three (3) forward in sufficient compartments so as to fulfill the DNV AUTRO requirements.

Power Generation System: The power generation system consists of an adequate number and capacity of generators located in two fully segregated engine rooms above the aft machinery spaces. The final rating of the generators will result from the electrical load balance where the following main scenarios will be considered and analyzed:

- Normal operation (DP + Hull utilities)
- Offloading operation (DP + offloading)
- Stand by (Unit in Heading Control situation + Hull utilities)
- Sail away (Unit in transit mode + Hull utilities)

The necessary power generation demanded by the process plant (topsides) of the FPSO will be generated by dual fuel gas/diesel turbines. The process plant is not considered to demand electric power from the FPSO Power Generation System.

Control System: The automatic thruster control consists of a computer system executing automatic thrust control to produce command output to the thruster. This is also the case after the occurrence of any single failure within the computer system or its associated equipment. The redundancy requirement that is necessitated by the DNV AUTRO requirements is to be accomplished by at least two parallel computer systems that can produce command outputs where one set is selected for transmission to the thrusters. The computer systems are to perform self-checking routines for detection of failure and if one on-line system detects a failure, an automatic transfer of on-line functions to the stand-by unit would take place.

A back up system is installed in the ECR and can be interfaced with a positioning reference that may operate independently of the main system. Manual control modes of the control system include control of thruster by individual control devices for pitch/speed and azimuth of each thruster, and an integrated remote thrust control by use of joystick.

Sensors: A position reference system with at least three position reference sensors will be provided to indicate position data with adequate accuracy. One of the systems will be part of the alternate control station in the ECR. Additional external sensors will be provided to supply necessary information for dynamic positioning. The sensors required by the regulations will include as a minimum two wind sensors, three Vertical Referenced systems (VRS), and three Gyrocompasses. One of each of the above listed sensors will be located in the alternate control station.

Disconnectable Turret and Riser System

The disconnectable turret and riser system is a very important component of the DP FPSO. The turret allows the vessel to weathervane about a single point to minimize environmental loads and motions of the vessel as a function of the environment intensity and duration. This allows the optimization of the thruster system, power consumption, and the motions of the vessel. The turret also allows fluid-transfer from the earth-fixed riser system to the ship-fixed production and storage system. Another important element of the turret-riser system is the ability to rapidly disconnect the vessel from the riser system when required.

Disconnectable turret mooring systems have been in use for many years, primarily in regions with frequent typhoons like the South China Sea and North-Western Australia. Most of these systems support a few risers and can be disconnected to allow the vessel to sail away and avoid a typhoon. The most sophisticated and complex disconnectable turret system has been installed in an FPSO on the Terra Nova field offshore Eastern Canada, (Duggal et al., 1999). This turret has been designed to support nineteen (19) risers and umbilicals, allow the vessel to stay moored in the severe 100-Year environment, and disconnect to avoid collision with icebergs. The vessel produces at a rate of 125,000 bbls/day, and has a storage capacity just under one million barrels of oil. This turret design forms the basis for the design of the turret system for this concept. The turret system is designed to disconnect from the riser system in a controlled manner with all risers depressurized and flushed in four (4) hours, and perform an emergency disconnect in less than fifteen (15) minutes. Figure 3 provides a schematic of the Terra Nova turret system. A detailed description of the turret and its operation are provided in Howell et al. (2000).

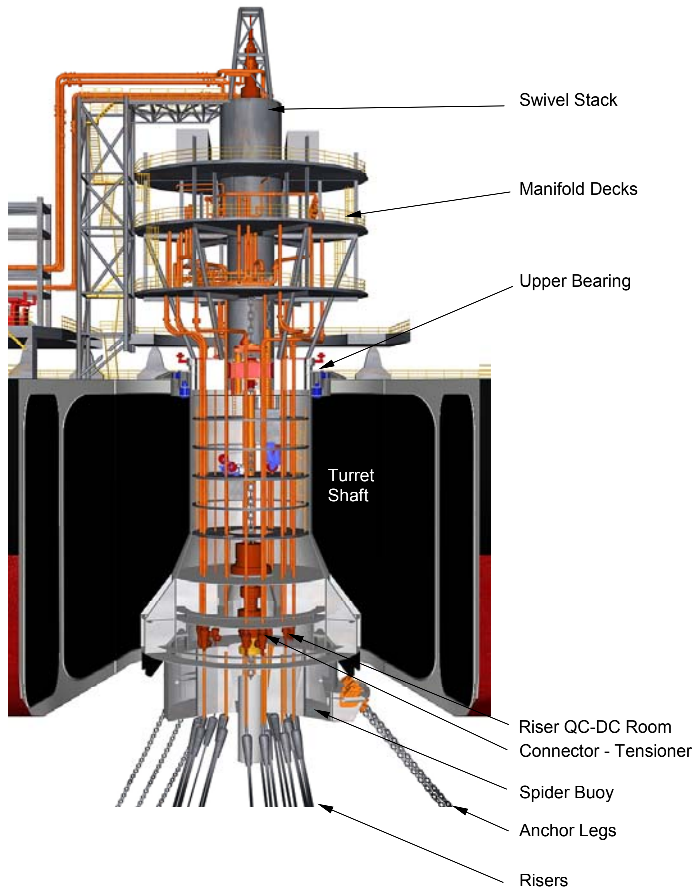

Figure 3. The Terra Nova disconnectable turret mooring system

From the figure it is seen that the disconnectable turret consists of three major components:

- **Disconnectable Buoy and Associated Systems:** The "spider buoy" is connected to the lower part of the turret by means of a large hydraulically activated mechanical connector that is preloaded so that the connection acts as a bolted joint. Above the buoy each riser pipe is fitted with a quick connect – disconnect (QC-DC) valve and connector system that allows rapid shutdown and disconnection of each riser. The buoy is released by disengaging the mechanical connector and allowing it to freefall to its equilibrium depth. The buoy retrieval system is self-contained in the turret (winch and chain-jack system).
- **Turret Structure:** The turret structure provides the load-transfer interface between the mooring and riser systems, and the vessel. The turret structure is provided with a bearing system at its interface with the vessel to allow it to passively weathervane about the mooring center. The turret structure also

provides support for the fluid-transfer system.

- **Fluid-Transfer System:** The fluid-transfer system includes the piping above the riser QC-DCs, the manifolding, the pig launching and receiving systems, and the swivel stack that allows transfer of fluids and signals from an earth-fixed system to a ship-fixed system.

Unlike conventional disconnectable turret mooring systems that depend on the anchor leg system to provide a means to support the riser system once the vessel is disconnected from them (e.g. Terra Nova), the DP FPSO system has to ensure that the risers support themselves when disconnected. This is a key feature of the disconnectable turret system designed for this application and requires the integrated design of the riser and turret systems.

For most field development scenarios it is unlikely that the risers will be arranged about the FPSO center in such a way that when a buoy supporting the risers is disconnected it falls to a stable equilibrium position below the surface, near FPSO center. Thus the turret and riser system have to be designed in a way that allows such a system to disconnect and fall to a stable equilibrium position regardless of the field layout. The solution developed for this application utilizes single leg hybrid risers (Petruska et al., 2002), or multi-riser towers as used on the Girassol field, that can be arranged at the desired distance and orientation from FPSO center to allow the system to be balanced, irregardless of drill center location, with very little economic and flow assurance impact. These risers consist of a vertical riser tower that is supported by a buoy near the surface. Flexible jumpers are used to interface between the FPSO and the riser as shown in Figure 4. Future risers can also be added in sequence to maintain this static equilibrium balance. Another important feature of this design is that the turret system is independent of water depth as the riser tower length is the water depth specific component. The length of the jumpers and the distance of the risers from the FPSO center can be maintained to be the same for all applications if required.

For the current example in the Gulf of Mexico (2,500 meter water depth) the turret-riser system is designed with twelve (12) single leg hybrid risers arranged on a 250 meter radius from FPSO center. Riser jumpers of length 425 meters are then used to connect the single leg hybrid risers to the buoy connected to the turret. For this application the buoy has a net buoyancy of 380 MT, and reaches a static equilibrium position approximately 200 - 250 meters below the water line, close to FPSO center. For the Gulf of Mexico it is important for the buoy to drop below the region of high current (loop current) to prevent extreme offsets requiring a depth of greater than 200 meters. For other field locations this stable equilibrium depth can be optimized based on the current environment. This concept has been successfully verified in the model tests described in the following section.

The remainder of the turret arrangement will be based on a layout very similar to that for the Terra Nova FPSO. Due to the reduced loads at the turret in the DP FPSO case (riser loads only, no mooring loads), the steel structure, mechanical connectors, and retrieval equipment for the DP FPSO will be much smaller than that used for Terra Nova. The fluid-transfer equipment will be similar to that shown in Figure 3 with manifolding, pig launching and receiving capabilities, and a swivel stack designed for the various fluids to be transferred. Due to the lack of a mooring system to counteract the friction in the system, and to minimize the "twisting" of the risers, the turret shall be equipped with a turret drive mechanism that ensures that the turret heading is maintained with the earth-fixed riser system.

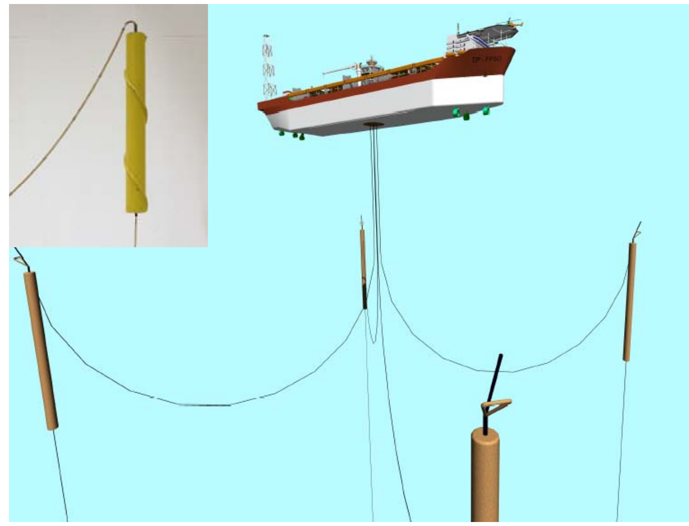

Figure 4. Schematic of riser system for DP FPSO

ANALYTICAL AND NUMERICAL MODELING

Prior to the model test program DP capability analyses and initial simulations were performed using the time domain simulation program DPSIM. DPSIM is used to study the behavior of dynamically positioned vessels, exposed to wind, irregular waves and current. DPSIM predicts the mean and low frequency motions in the horizontal plane and provides mooring line loads (if used), thruster, propeller and rudder forces, and estimates of power consumption. Based on these simulation results the model test program was optimized and initial DP control settings were established.

Current loads were based on current load coefficients of a similar shaped FPSO and a constant current velocity. Wind loads were calculated using wind load coefficients of a FPSO with similar hull shape and topsides and assuming a NPD wind spectrum formulation. For the second order wave loads a diffraction analysis was performed on the DP FPSO. All of this data, including thruster characteristics and positions, were used as input into DPSIM and simulations run for the various environmental conditions presented in Table 1.

A standard PID controller was used to calculate the required thrust. The initial control settings for surge, sway and yaw were determined as follows:

- *Spring Coefficient:* Maximum. total thrust / max allowable excursion.
- *Damping Coefficient:* 70% of critical damping
- *Integrating Coefficient:* zero

With these settings a large number of simulations were performed to optimize the control coefficients. As sway and yaw are highly coupled, a good balance has to be found between these coefficients. The integrating coefficient was purposely set to zero as it only reduces the static offset and the main focus of the study was to study and optimize the motions of the DP FPSO.

The calculated thrust by the controller was allocated over the available thrusters using a thruster allocation routine based on LaGrange multipliers and minimizing the total consumed power. Three different allocations were used:

- Full DP, with all six thrusters active
- Maximum single failure (CL fore and aft thrusters inactive)
- Four thruster inactive (only CL fore and aft active)

The third allocation simulates a maximum single failure in light sea states, when only four thrusters are used to maintain position (and the other two are out of service, e.g. for maintenance).

MODEL TEST PROGRAM

Early 2003 an extensive model test program on the DP FPSO has been completed in MARIN's deep water Offshore Basin. The tests were performed at a scale of 1 to 60. The modeled water depth in the basin was 600 meters. The DP FPSO model was equipped with a disconnectable buoy and six azimuthing thrusters, in a thruster layout with three thrusters both forward and aft. Figure 5 shows the model as used in the model tests.

Figure 5. DP FPSO model with disconnectable buoy

The thrusters were controlled using a dedicated real-time full DP-system ('RUNSIM'), including an extended Kalman filter. Using this control system the DP FPSO was free to choose any heading set point in order to minimize the motions or power consumption. The turret was equipped with a heading control system, allowing the buoy to maintain its earth-fixed orientation independent of the DP FPSO heading.

An equivalent riser system for 2,500 meters water depth was installed in the basin. The riser system consisted of four (4) truncated vertical riser towers (each modeling 3 individual risers), up to 250 meters below the water surface. Each riser had a cylindrical air can to obtain the required pretension. The connection between the top of the air can and the disconnectable buoy was made with flexible jumpers. The design of the riser system was such that after disconnection from the FPSO the buoy dropped to a depth of 250 meters below the water line, to avoid excessive current loads. Figure 4 shows a schematic view of the model test setup, with the air can model in the inset.

The model test program focussed on Gulf of Mexico environmental conditions. The environments were simulated by generating waves, wind and current in the model basin. The test program considered the following sets of tests:

- Normal operational conditions
  - 90% exceedance (Hs 2 m / Tp 6 s)
  - 99% exceedance (Hs 4 m / Tp 9 s)
- Survival conditions
  - Loop current (Vc = 2.13 m/s)
  - 10-Year winter storm (Hs 5.8 m / Tp 10.6 s)
  - 10-Year Hurricane (Hs 8.6 m / Tp 12.3 s)
- Squall conditions
  - Wind gusts to 30 m/s with change in direction
- Offloading to shuttle tanker
  - 90% & 99% exceedance sea states
- Disconnect and connect procedure
  - Disconnect in 10-Year hurricane conditions
  - Reconnect in 90% exceedance conditions
- Free drift or hovering tests
  - 100-Year hurricane conditions (Hs 12.5 m /Tp 13 s)

For each condition the range of headings was determined where position keeping is possible. This was done by performing short tests at 5-degree heading intervals. For the heading with the lowest thrust requirement a 3-hour test was performed to obtain statistics on power consumption and position accuracy.

MODEL TEST AND NUMERICAL RESULTS

The first step was to assess the DP capability of the FPSO based on mean environmental loads. DP-capability plots were made for all selected sea states, loading conditions and thruster allocations. A typical example is shown in Figure 6 for the 10-Year winter storm condition and allocation for six thrusters (blue), four thrusters (red) and two thrusters (green). In these calculations a margin for dynamics has been used to account for the fact that a quasi-static approach is used to predict the dynamic behavior of the vessel.

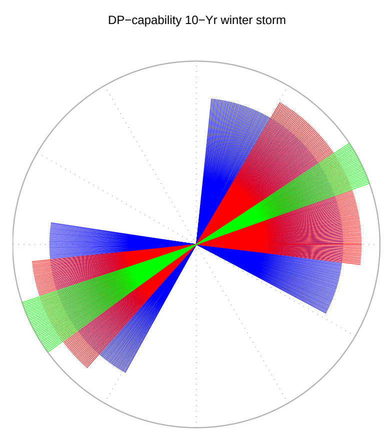

Figure 6. DP-capability plot for 10-Year winter storm condition

It is obvious that the use of six thrusters results in a higher capability than four or two thrusters. Use of only two thrusters results in a marginal DP capability and is not further investigated. Figure 7 shows the results of the time domain simulations for the same condition. The simulations were done in 5-degree intervals until a drift off was observed. The trend in capability is the same, but the range of headings where the FPSO is able to maintain position is smaller. Apparently the dynamic effects are higher in this sea state than anticipated in the quasi-static approach.

Based on the time domain simulations a heading range of -15 to +10 degrees is predicted. Figure 8 shows the model test results plotted on the same scale. The motions in the model tests are larger due to the wave frequency motions (which are not included in the time domain simulations) and the effect of the Kalman filter. However, the range of allowable headings for both simulations and model tests are identical. Total power consumption for simulations and model test shows the same trend, but the required power in the model tests is somewhat higher.

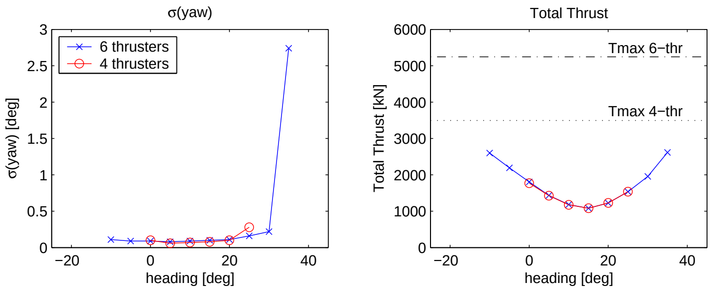

Figure 7. Results of DP simulations in 10-Year winter storm condition

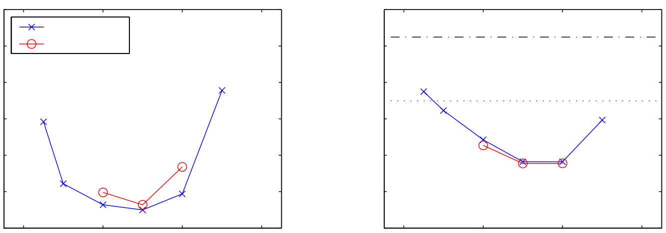

Figure 8. Results of DP model tests in 10-Year winter storm condition

The results of the model test program show that the DP FPSO concept is very encouraging. The main findings are:

- In the 90% exceedance sea state only two thrusters are required to maintain position. This allows maintenance on the thrusters for most of the year while still having sufficient redundancy. Based on the required thruster power in these tests it can be concluded that the fuel consumption most of the time is very small.
- In the 99% exceedance sea state position keeping with four (4) thrusters is excellent. This means that even with a maximum single failure position keeping will still be good.
- The test in squall conditions show that position can be kept provided the vessel heading is turned into the direction of the squall wind in time. It is not possible to maintain position with a squall beam-on. Figure 9 shows a typical squall maneuver where the vessel turns into the wind before the maximum wind speed is reached.
- The offloading tests were done with a traditional shuttle tanker connected to the FPSO by a bow hawser. Back thrust was applied to avoid fish tailing of the shuttle. Due to the hawser load this can be considered a worse case for the DP FPSO. It is most likely that shuttle tankers in the GOM will be DP operated; however, in West Africa and Brazil they will most probably be conventional trading tankers. Therefore the offloading tests are considered to be conservative. The position keeping during offloading in 90% and 99% exceedance sea states was excellent, using only four thrusters. This means that even in offloading conditions a maximum single failure can be dealt with. Figure 10 shows a typical plot of the offloading of the DP FPSO in 90% exceedance crossed condition (Hs = 2 m). The DP FPSO has virtually no motions, whereas the shuttle tanker shows some fishtailing.
- To show feasibility of the disconnect procedure tests were performed in the 10-Year hurricane condition, where the disconnectable buoy was released from the turret. These tests were repeated at different times in the wave sequence and the behavior of the buoy was observed with an underwater camera. The buoy showed a very predictable behavior and dropped quickly from the FPSO. No impacts were observed between buoy and keel of the FPSO. The photo sequence in Figure 11 shows how the buoy is released during the disconnect procedure in 10-Year hurricane conditions.

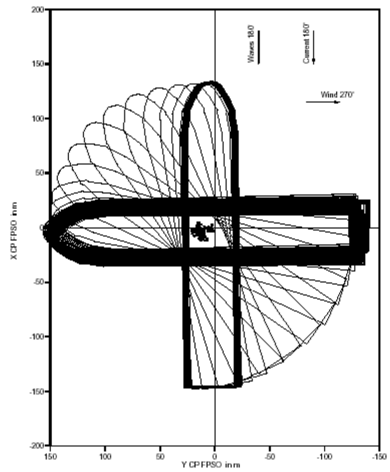

Figure 9. Squall maneuver.

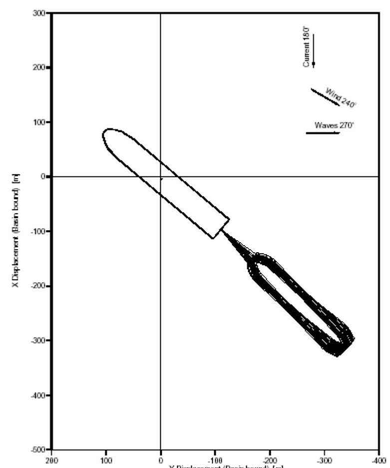

Figure 10. Offloading of DP FPSO to a conventional shuttle tanker.

- Tests of the reconnect procedure in the 90% exceedance sea state showed no difficulties either.
- In survival sea states (loop current and 10-Year Hurricane) all six thrusters are needed to maintain position. Figure 12 below shows the DP performance in the 10-Year hurricane condition. The excursions of the DP FPSO are mainly in surge direction. Although the range of headings where position keeping is possible is limited in these conditions, position accuracy is still very good and well within the limits of the riser system.
- The free drift tests were performed in 100-Year Hurricane

conditions, with the buoy disconnected. In this condition the vessel is able to maintain its heading, but not able to maintain position above the riser pattern. Based on these tests the drift speed was determined in order to calculate the time available for an emergency disconnection procedure.

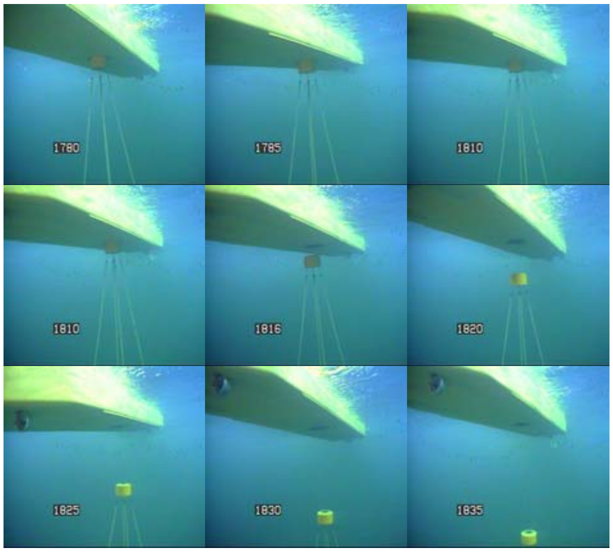

Figure 11. Disconnection of the riser buoy from the turret

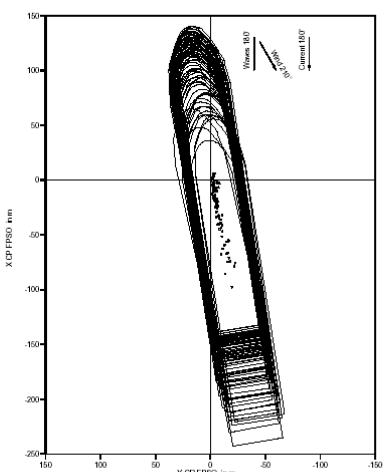

Figure 12. DP positioning in 10-Year hurricane conditions

Based on the model test results the numerical model was tuned. With this tuned numerical model more accurate simulations can be performed for other environments than those tested in the model test program. Also a full simulation study on a second size FPSO is foreseen. Table 3 compares results from the model tests and the tuned time domain simulations for two environmental conditions.

There is reasonable agreement between simulations and model tests. A complicating factor in the comparison between model tests and time domain is the presence of the disconnectable buoy and the riser system that is not completely modeled in the DPSIM simulation. The current loads on and damping due to this system is fairly large and difficult to predict and have not been accounted for in the preliminary engineering of the system.

Table 3. Comparison between simulation and model test results

Environment	90% exceedance		10-Yr winter storm	
	DPSIM	model test	DPSIM	model test
mean X	-7.5	-5.6	-15.8	-9.8
stdev X	0.2	0.4	1.8	3.3
mean ψ	16.3	16.0	10.3	10.1
stdev ψ	0.1	0.2	0.2	0.3
mean power	1086	755	4813	6699
stdev power	128	367	1384	3501

SUMMARY AND CONCLUSIONS

Offshore production faces a continuous challenge to keep pace with aggressive drilling programs in ultra deep waters. Only just a few years ago industry celebrated a well drilled in 2,000 meters water depth. Today industry is already targeting exploration in 3,000 meters

The DP FPSO concept proposed in this paper is an innovative solution to meet this and other challenges in a cost efficient way.

The development project is organized in as a JIP project and will address the key issues related to offshore production on DP, including the reliability of the DP system and the regulatory compliance (Cortijo, et al. 2002). Information on the risk and reliability studies, and regulatory development work is outlined in (Cortijo, et al. 2003). The JIP is still in progress but already has demonstrated the feasibility of maintaining a large FPSO on position in extreme conditions in the Gulf of Mexico using a DP thruster system. The feasibility of the disconnectable turret riser system has also been demonstrated in the model test program.

Current work focuses on the completion of the stationkeeping simulations, and completion of the engineering of the FPSO vessel, and the disconnectable turret riser systems. Work is also underway in performing a reliability study of the DP thruster system, and ensuring compliance with the regulations in the various target regions. Future work will focus on developing a DP early production system, building off the experience developed from the Gulf of Mexico FPSO, and a detailed life of field cost analysis comparing a conventionally moored FPSO versus a DP FPSO in ultra deep water.

REFERENCES

Brink, AW, and Chung, JS (1981), "Automatic Position Control of a 300,000 Tons Ship during Ocean Mining Operations," *Offshore Technology Conference*, OTC 4091.

Cortijo, JL, Duggal, A, van Dijk, R, Matos, S (2003), "A New Solution for Floating Production in Ultra Deep Waters," *Offshore West Africa Conference*.

Cortijo, JL Lago, F. and Mendez, A (2002), "New FPSO-Based Concepts for the Deep Water Challenge", *17th Annual Conference on Floating Production Systems*, UK.

Duggal, A, Heyl, CN, Vance, G (2000), "Global Analysis of the Terra Nova FPSO Turret Mooring System," *Offshore Technology Conference*, OTC 11914.

Gardner, G. (1999), "Practical Experience of FPSO and Offtake Tanker Station Keeping", *IMCA Station Keeping Seminar*, France.

Henriques, CCD (2000), "Petrobras Experience on the Mooring of Conventional Shuttle Tankers to Dynamically Positioned FPSOs", *Proceedings of the 10th ISOPE Conference*.

Howell, G., Duggal, A. and Lever, G (2001), "The Terra Nova FPSO Turret Mooring System," *Offshore Technology Conference*, OTC 13020.

Petruska, DJ, Zimmermann, CA, Krafft, KM, Thurmond, BF, and Duggal, A (2002) "Riser System Selection and Design for a Deepwater FSO in the Gulf of Mexico", *Offshore Technology Conference,* OTC 14154.

Wichers, JEW and van Dijk, R (1999), "Benefits of using Assisted DP for Deepwater Mooring Systems", *Offshore Technology Conference*, OTC 10781.