DP Assisted Offloading Operations in Brazilian Water

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ABSTRACT

In this paper, several aspects regarding DP assisted offloading operations in Brazilian Waters are discussed. The main objective of such work is to define a more accurate set of premises to the design of the DP System of the new Shuttle Tankers (ST) that will operate in Brazilian waters and to expose the actions that Brazilian scientific and industry communities are taking to define those premises.

Initially, important issues of the Brazilian regulatory guideline related to the operation are addressed, focusing on the safety procedures and DP-ST design requirements. Full scale measurements of a DP offloading operation were done, considering all stages of the operation: approach to the FPSO, connection, oil transfer and disconnection. The results of such monitoring campaign were used to validate the Numerical Offshore Tank time domain simulator (TPN), and the main results are presented in the paper. Some numerical studies concerning comparison between DP and non-DP offloading operations are presented. Such studies were carried out using the TPN simulator, considering normal situations, extreme environmental conditions and failure scenarios. A procedure to evaluate the operational downtime, based on numerical simulations is also presented. Small scale model of typical Brazilian DP-ST’s were also built, and ocean basin experiments were done. Preliminary results are discussed. Finally, novel research topics related to such operation are addressed, related to the hydrodynamic and aerodynamic interference between the FPSO and the ST. Computational fluid dynamics (CFD), small scale experiments and numerical models are being used to evaluate the impact of such effects on the dynamics of the ST and on the DP System power requirement.

1. INTRODUCTION

In Brazilian waters, 14 Turret-moored and 9 Spread Moored FPSOs keep on producing oil and the interval among loadings corresponds to 5 days on average, with more than 600 off takings performed by year. As a result of the installation of more FPSOs in Campos Basin until the end of this year, the number of loadings will considerably increase. On condition that most of them will be moored in a spread system, and considering that the results of a preliminary risk analysis for this kind of unit recommended the use of DP tankers as a measure to reduce the risk collision, the demand for more DP tankers should be carefully studied. At the present time, there are 9 DPSTs (TRANSPETRO) plus other 3 hired abroad, totaling 12 DPSTs operating for PETROBRAS in Brazilian Waters, confirming its high operational efficiency on the offshore terminals and on the onshore terminals as well. The total operational time has been reduced in 35% on average compared to the conventional trading tankers. The time for mooring and hose connection phases are significantly decreased. Others operational phases have been carried out at any time (operations during the night) reducing the time spent in general.

The decision on the use of DP-ST comes from 1994. In that time, planning to implement DP operations in a short time, PETROBRAS decided to convert vessels instead to build new hulls and faced with a constraint. The alternative to buy a DP Class-2 was put aside, once there were no STs provided with DP Class-2 available for purchasing. The option to adapt a standard tanker in a DP Class-2 is feasible, but the costs involved would be much higher (maybe prohibitive) than the costs to convert a conventional tanker in a Class-1 or an “enhanced” Class-1. The technical committee agreed that DP Class-1 was an acceptable standard but should be provided with redundancy in several systems, representing an “Enhanced” class. Some systems in the regular DP Class-1 were selected to provide an appropriate degree of redundancy to minimize lost of position or blackout occurrences from single failures. These redundancies derived from the failure statistics and the operational experience with DP Drilling Rigs in Campos Basin.

Despite this original strategy to speed up the DP Shuttle Program implementation, Petrobras is now analyzing the DP Class II as a minimum for the new vessels contracted from now on. With this constantly evolution scenario, Petrobras has started cooperative programs with Brazilian scientific community, in order to carry out experimental and numerical studies to support important decisions about regulation and operational requirements for the offloading systems and vessels. Such works resulted in important design and analysis methodologies as well as design tools, such as time-domain simulators and experimental facilities.
2. PETROBRAS GUIDELINES FOR DP SHUTTLE TANKERS

While the phase of renewing the ST fleet is in progress, DP and the conventional tankers had offloaded the FPSOs in Campos Basin, apart the main offloading hose string system exclusively dedicated for BLS connections, it becomes necessary to keep a hose string (an emergency hose) permanently connected at the FPSOs and ready for midship manifold operations (to attend conventional tankers). It implied an unusual adjustment on the FPSO’s discharge system, with the FPSOs keeping its emergency hose string mounted. In order to minimize these undesirable adjustments, due to logistics and the maintenance program increasing the overall operational cost, PETROBRAS selected some FPSOs to operate with DPSTs only. Fig. 1 shows photos of the offloading operation with conventional and DP Tankers.

The Crude oil business added a huge amount of cargo for exportation, what requires an equivalent storage and transportation capacity. The internal Technical Committee has recommended a DPST fleet to serve the FPSOs dedicated to Campos Basin. Further the offloading by means of VLCC size is definitely prohibited and established the use of the Suezmax type as a maximum shuttle size.

With the intention of maximizing off takings by DP tankers, PETROBRAS has tested STS (Ship-to-Ship) operations in open sea, close to Campos Basin region. A DPST (DP Shuttle Tanker) perform the loading from the FPSO, transferring the oil in sequence to a trading tanker (VLCC or Suezmax size), which will export the cargo. Typically, the operational time is significantly reduced making use of the positioning capability of the DPSTs, not requiring masters, tugs or any external resource. Their thrusters and well-trained crews are as much as necessary to carry it out.

Oil loading in open seas must be performed by well-trained personnel on the ST and the FPSO and operational procedure shall be followed and well prepared. The internal Technical Committee prepared the document “Campos Basin Offshore Loading Guideline for DP Shuttle Tankers Operations”. This document is a guideline with information, requirements, guides and procedures involving oil field, offshore terminals, responsibilities and duties, DPST, safety, operational sectors, operational limits, maneuverings, mooring, emergency and offloading operation.

In the document operational zones (or sectors) for the offloading operation from a Turret or Spread Moored offshore terminals, as an F(P)SO, to a DPST procedure in are define:

- Operational Sector (Green zone): This is a sector established in relation to the Offshore Terminal (for instance a F(P)SO) centerline. Within this sector the DPST is allowed to weathervane freely while offloading.
• Alert Sector (Yellow zone): Within this zone the Captain is allowed to stay just the time to attempt bringing the DPST back to the operational sector. Reaching the border line, the DPST Captain has to contact the F(P)SO OIM requesting the offloading immediate interruption. The DPST Captain shall initiate the first stage of the offloading emergency shutdown procedure and be ready to actuate the emergency disconnection of the offloading hose line from the BLS and the mooring system using the second stage of the emergency shutdown procedure.

• Disconnection Sector (Red Zone): Within this zone the DPST is not allowed to stay. Reaching this sector, the DPST Captain has to initiate the second stage of the OESD (Offloading Emergency Shut Down) disconnecting the offloading hose line from the BLS and the mooring system.

These limits are differently defined for Turret or Spread Mooring FPSOs, as indicated in Fig. 2.

![Fig. 2. Sectors definitions for: (left) Turret Moored FPSO; (right) Spread Moored FPSO](image)

The guideline for DPST operations established two operational modes, the Taut Hawser and the Full DP mode. In the Taut Hawser mode the position is kept in “Manual Mode” via DP system (preferable) or via the individual thruster lever console, by controlling position and hawser tension “manually”. The Captain can ensure the distance between the FPSO and the DPST using the main propeller with a small thrust astern and keeping the hawser tension up to 20 ton according to the intensity and direction of the environmental forces. This mode is used when no RPRSs (Relative Positioning Reference System) are available or occasionally during offloading in Full DP mode.

Full DP is the main operational mode. The goal is a more “relaxed” weathervane station keeping with less thruster activity. In this mode a “rectangle of operation” is defined according with the limits of surge, sway and relative heading. As long as the offloading point remains inside the rectangle, the Shuttle Tanker neglects small “surge” or “fishtailing” motions of the F(P)SO. The operation combines the absolute position, given by the DGPS (instantaneous station keeping) with relative position given by the PRS (Positioning Relative System: DARPS, Artemis, Fanbeam). The motion of the “offloading point” in the production unit is controlled by this “rectangle of operation”. The F(P)SO stern position can move within the rectangle without the shuttle tanker executing any position correction. If the F(P)SO moves outside the border of the rectangle, the rectangle is moved to the actual vessel position and the shuttle tanker set point is updated accordingly.

The storage units, F(P)SOs, are moored by a turret or in a spread system. The offloading point is located at the stern of the F(P)SO in turret mooring and at the stern or the bow in the spread mooring system, so that the offloading operation is carried out with the shuttle tanker automatically “weathervane” around the F(P)SO. Thus, in general, the relative heading is more important than the absolute vessel heading. However, during the approach maneuvers, the control of the relative ship’s heading is very important to optimize this critical phase of the operation and also to avoid “blind sectors” in the RPRSs.
As already mentioned, the philosophy adopted by PETROBRAS’s Technical Committee is to provide a suitable redundancy level(s) to minimize the position loss with or without control due to single point failures. Combining a proper safety level and an excellent operational efficiency, the “Enhanced” DP Class-1 definitely represents the most cost effective alternative regarding to the market, when is imperative to implement DP operations in a short term. Despite this original strategy to speed up the DP Shuttle Program implementation, Petrobras is analyzing the DP Class II as a minimum for the new vessels contracted from now on. Finally, the ST basic requirements for operation in Brazilian waters were made focusing on the Engineering Analysis, general design data (weather conditions, minimum deadweight, etc.), loading systems, propulsion configuration, power generation, DP control system and trials.

Regarding the Engineering Analysis, the following items has been required by PETROBRAS:

- FMEA (Failure Mode and Effect Analysis) for DP system (Power Generation, Propulsion Plant and Controls) comprising a theoretical study and a conclusive report based on the field tests (DP e Proving Trials).
- Preliminary Static Analysis drawing Capability Plots taking into consideration the propellers 100% available and individual failures on each one.
- Complementary Time Domain Analysis (checking the ship dynamics, operational sectors, hawser tension occurrence, etc). Concerning the environmental loads, the waves, wind and current should be considered acting simultaneously and aligned according to the worst case. The statistics of the one-year return period shall be used.

Concerning the Oil Loading System, PETROBRAS required a field proven BLS to operate with submarine and floating hose types and a console installed on the bridge suitable to control the BLS operations. Further, two decks are required as well on the bow, one for mooring/chain stopper and a second one for the handling winches. A conventional traction winch 50t and a 300t SWL chain stopper are required for mooring.

Maneuverability and positioning capability are important features for oil transfer between shuttle tankers and F(P)SO. High maneuverability should be required to provide a watchful approach and to keep the position when loading moored to the F(P)SO. Most of the shuttle tankers are provided with twin bow thrusters, stern thruster, a controllable pith main propeller and a flap rudder. On the other hand, regular tankers are usually equipped with one-shaft line only. Thus, the propulsion configuration requested by PETROBRAS comprises of one (01) CPP, two (02) bow thrusters (1 azimuth and 1 tunnel), one (01) stern thruster and one (01) high lift rudder. The feasibility of the installation of a second stern thruster should be also verified. The intention of having an azimuth thruster is to provide proper redundancy to allow the ship to leave the operation area just in case of failure of the main propeller.

In view of the “Enhanced” DP Class I philosophy previously mentioned, PETROBRAS specifies for the Power Generation, Distribution, Protection and Management Systems, the following configuration:

- Redundancy levels to minimize blackout from a single failure
- Satisfactory power generation for thrusters, BLS and other systems, considering:
- 1 Diesel-Generator of the original Power Plant in “Hot Stand-by” condition
- Primary equipment and systems for offloading operation 100% loaded (???)
- Redundant transformers to feed essential peripherals of diesel generators, thrusters, main engine, CPP and some auxiliary equipment
- Dedicated UPSs for automation, supervising, protection and controls of Power Generation/Distribution Systems and Propulsion System (pitch/azimuth control, and others 120 VAC, 110 VDC or 24 VDC consumers)
- Power Management System (PMS) integrated to the DP system
• Dynamic Positioning Control System (Controllers, PRS, Sensors, Data Monitoring and Storage System and UPS)

With regards to the existing tankers, PETROBRAS has recommended a “dual” power generation arrangement (“Old” Power Plant + “New” Power Plant). A full autonomy for the “New Plant” is required. For redundancy purpose a connection between the “Old Plant” and the “New Plant” is also required (bus bar).

For the Dynamic Positioning System (Controllers, PRS, Sensors, Data Monitoring and Storage System and UPS) the basic requirements are the following:

• Controllers: DUPLEX configuration for computers and consoles (two independent systems automatically operated in Master/Slave condition)
• Operational modes required: Manual Mode, Auto-Position Mode, Approach Mode, Weather Vane Mode e Tandem Mode
• Positioning Reference Systems: Artemis MKV, DARPS 700 (or the more recent DARPS 232) and Fanbeam (Multiple Target software included)
• DP Sensors: 02 gyros, 02 VRUs – Vertical Reference Units (Roll & Pitch), 02 anemometers and 01 interface with the Draft Indicator System
• Independent UPSs for the DP system

3. FULL SCALE MEASUREMENTS OF A DP OFFLOADING OPERATION

Full scale measurements of a DP offloading operation were carried out, considering all stages of the operation: approach to the FPSO, connection, oil transfer and disconnection. DP-ST motions, thruster forces and environmental agents were measured. The time-domain offshore system simulator (TPN) was then used to reproduce the same conditions of that operation, and the results from the numerical code are compared to the full-scale measurements. Good agreement between numerical results and full-scale measurements was observed, and the main results of such campaign are exposed in this section. Detailed description of this work can be found in Tannuri et al. (2009) and Saad et al. (2009).

The DP Shuttle Tanker (Aframax Vessel) and FPSO (Mono-Column Platform) main characteristics are presented in Table 1. The DP Shuttle Tanker is equipped with 5 thrusters, indicated in Table 2.

<table>
<thead>
<tr>
<th>Property</th>
<th>FPSO</th>
<th>Shuttle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>65.1 m</td>
<td>229.0 m</td>
</tr>
<tr>
<td>Beam</td>
<td>65.1 m</td>
<td>42.0 m</td>
</tr>
<tr>
<td>Draft Full</td>
<td>18.0 m</td>
<td>14.3 m</td>
</tr>
<tr>
<td>Draft Ballasted</td>
<td>11.2 m</td>
<td>5.3 m</td>
</tr>
<tr>
<td>Depth</td>
<td>27.0 m</td>
<td>21.3 m</td>
</tr>
<tr>
<td>Displ. Full</td>
<td>54276 MTons</td>
<td>117020 MTons</td>
</tr>
<tr>
<td>Displ. Ballasted</td>
<td>34315 MTons</td>
<td>39900 MTons</td>
</tr>
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Table 2 DP-ST Thrusters

<table>
<thead>
<tr>
<th>Thruster</th>
<th>Thrust</th>
<th>Power</th>
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<tbody>
<tr>
<td>1- Tunnel Bow</td>
<td>28tonf</td>
<td>1935kW</td>
</tr>
<tr>
<td>2- Azimuth Bow</td>
<td>36tonf</td>
<td>2000kW</td>
</tr>
<tr>
<td>3- Azimuth Stern</td>
<td>36tonf</td>
<td>2000kW</td>
</tr>
<tr>
<td>4- Tunnel Stern</td>
<td>16tonf</td>
<td>1050kW</td>
</tr>
<tr>
<td>5- Main Propeller</td>
<td>220tonf</td>
<td>18891kW</td>
</tr>
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</table>

The mean environmental parameters during the offloading operation corresponds to: wave coming from east with 2.5 significant height; wind velocity had changed from 8 knots up to 25 knots coming from southeast; and 0.7 knot current velocity going to south. Time series of environmental conditions intensities are shown in the Fig. 3.

Fig. 3 shows the foot prints positions of the shuttle tanker ship and the mono-column FPSO, recorded during the offloading operation.
The main operation stages are:

- **Approach (a)** – The shuttle reduces her speed and changes her heading in the approach to the FPSO. The relative heading between the platform and shuttle is around 10 degrees to allow for an emergency exit.

- **Hose Connection (b)** – The relative distance is around 100m to allow the shooting of the air gun and the messenger line transfer, and after that the hose connection to the bow load system. This operation was done in “full DP” mode without hawser hook-up.

- **Weathervane Heading (c)** – At this point the Captain has selected the weathervane mode, resulting in some heading changes in order to best align the ship with the resultant of environmental forces, minimizing the power required to hold position during cargo transfer. The non-directional characteristics of mono-columns hulls may allow for a bigger operational sector and a higher weathervane position range providing a safer operation.

- **Offloading (d)** – Shows the tanker’s position held while the oil was transferred. It can be seen the negligible variation in the tanker position, that is keeping station having the FPSO as reference. In doing so, the ship ignores the first order environmental loads, which is typical of DP vessels.

- **Disconnection (e)** – During this step, the transfer is completed and the FPSO retrieves the hose back to the reel. The ship starts to move backwards.

- **Sailing (f)** – Finally, the ship reaches a safe distance to change her heading and starts off to the oil terminal.

A more detailed analysis of a 1-hour time period during hose connection, (before the heading correction - Fig. 3-b) and after the heading correction (Fig. 3-d) is presented. The mean environmental conditions during those two stages are presented in the Fig. 4. The directions are related to the True North axis. The wave is characterized by the significant height (Hs) and zero-crossing period (Tz).
During the whole campaign, DP total forces are measured, as well as individual thruster forces. Furthermore, the same environmental conditions exposed in Fig. 4 were used as input for the time domain simulator TPN (Numerical Offshore Tank). Detailed description of the TPN simulator is presented in the Appendix. Table 3 shows the mean values of thrusts in those two stages, indicating that in fact the new heading minimizes the required thrust. Fig. 5 shows the time series of the sway force, in which can be noticed the reduction of the control demand after the heading change.

Table 3 Mean Total Control Forces and Moment

<table>
<thead>
<tr>
<th></th>
<th>Real Scale Measurements</th>
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<th>Simulation</th>
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<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
</tr>
<tr>
<td>Surge Thrust (tonf)</td>
<td>4.3</td>
<td>3.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Sway thrust (tonf)</td>
<td>28.5</td>
<td>10.2</td>
<td>26.7</td>
</tr>
<tr>
<td>Yaw Moment (tonf.m)</td>
<td>592</td>
<td>306</td>
<td>527</td>
</tr>
</tbody>
</table>

Comparison between real-scale measurement and simulation results indicates that:

- the simulation was able to predict the benefits of the heading change, since the total demanded thrusts are reduced after the maneuver;
- the total sway force is predicted with good accuracy by the simulator (differences of 6%);
- the total yaw moment is predicted with acceptable accuracy by the simulator (differences of 18%);
- the total surge force is roughly predicted (maximum difference 86%).
Several reasons may explain such observations. Numerical prediction of surge forces is normally more imprecise, when compared to sway force. For surge forces, for example, complex viscous effects are relevant. Other important aspect is the aerodynamic interference between the platform and the vessel. Such effect is not considered in the simulations, and should have played an important role in the full-scale measurement, since the shuttle tanker is exactly in the shadow zone defined by the platform (see Fig. 4).

Forces delivered by each thruster are also measured. Mean values for the 1-hour before and after the heading change are shown in Fig.7. The reduction of thrust demand can be again verified. Again, comparison between real-scale measurement and simulation results indicates good agreement between the thruster allocation logic, mainly considering qualitative aspects of the thrust distribution.

![Fig. 6. Mean forces delivered by each thruster: (left) real-scale measurement (right) simulation](image1)

In order to illustrate DP wave filter performance, the time series of the bow azimuth thrust is indicated in Fig. 7. The power spectrum of the thrust is given in Fig. 8. It can be verified that the oscillations of the time-series are in the frequency range of slow-frequency motions of the vessel. It indicates that the first-order motions are well attenuated by DP wave filter algorithm. A rough comparison between real-scale and simulation results indicates that, despite a difference in mean value (already explained), the overall behavior is quite similar. In fact, the standard deviation of the full scale thrust is 2.75tonf, compared to 2.86tonf in the simulation result. Power spectrum proves the good performance of the wave filter, and an acceptable agreement for frequencies larger than 0.01Hz can be verifies. The tuning of wave filter parameters could make such agreement better for low frequencies.

![Fig. 7. Thrust delivered by bow azimuth propeller: (left) real-scale measurement (right) simulation](image2)
As demonstrated, a good agreement between numerical results and full-scale measurements was observed, what indicates that the computational simulator is an effective tool in the analysis and design of DP systems applied to offloading operations.

4. COMPARISON BETWEEN DP AND NON-DP SHUTTLE TANKER: NUMERICAL ANALYSIS

In this section, some illustrative numerical analyses are presented, related to the utilization of the time-domain simulator (TPN) as a design tool for DP offloading operations. The studies have also stressed the advantages of using a DP ST compared to the conventional tug-assisted ST.

4.1 Failure consequence analysis

The simulator was used to evaluate the consequences of typical failures in DP and non-DP offloading conditions. Some illustrative results are presented here.

The first case is the failure of the main engine during the connection stage. Fig. 9 shows that for the conventional ST, such failure makes the ST to lose position causing a large force in the hawser. A disconnection must be then executed. For the DP-ST, the consequences of such failure are not severe, since the azimuth thrusters may produce the required longitudinal force, replacing the main propeller action. Those simulations were executed considering a typical Campos Basin environmental condition during the winter, and a Suezmax class shuttle tanker.

Fig. 9. Failure of main engine during connection: (a) system configuration; (b) conventional ST – trace-plot and hawser tension; (c) DP-ST trace plot and thrusts (3) – stern azimuth and (4) – main propeller
The second case is the failure (rupture) of the cable connecting the tug-boat to the non-DP ST, followed by a failure in main propeller, due to the sinking of such cable that may get wrapped around the main propeller. Fig. 9 shows that such a failure may cause a collision, depending on the direction of the environmental forces.

Fig. 10. Rupture of tug cable and failure of main propeller: (left) system configuration; (right) conventional ST – trace-plot

The third case corresponds to the blackout and drive-off failures of the DP-ST. Such catastrophic failures may cause collision, Fig. 11a shows that blackout may cause a collision, depending on the direction of the environmental forces. Furthermore, the simulation is also used to evaluate the path of the vessel after the drive-off (b) and the time between the drive-off failure and the collision (c).

Fig. 11. DP-ST (a) blackout; (b) drive-off: trace plot; (c) drive-off: time to collision analysis

4.2 Environmental change

The environmental conditions in Campos Basin can be considered fair most of the time, moderately good from November to March, variable from April to June and relatively severe from July to October. Northeast winds with intensity around 16.0 knots (8.2 m/s) on average are dominant but Northeast winds of 40 knots (20.6 m/s) are normally observed. Special care must be taken in relation to the cold masses arriving from Southwest, generating sudden changes in wind direction, from NE to SW, and in intensity with gusts up to 55 knots. This occurrence is more likely to happen in autumn (March to May) and spring (September to November). Such situation may require the interruption of the offloading operation, mainly for the non-DP ST, as indicated in the simulations presented in Fig. 12 (conventional ST) and Fig. 13 (DP-ST).
4.3 Downtime estimation

In this section, a methodology based on fully-dynamic simulations is presented for evaluating the
downtime of the offloading operation, considering a typical Suezmax ST, in both a Turret and Spread
Moored FPSO in Campos Basin.

The operational downtime is normally estimated by a naive procedure. After designing the DP vessel to
withstand the limiting environmental conditions, the Metocean data (scatters of wind, waves and current)
of the region is analyzed and the occurrence of conditions with wave, wind or current above the limiting
condition defined in DP design are estimated. Such total occurrence is considered the downtime of the
operation. Of course, the premise of this procedure is that the DP design was done with a high level of
accuracy.

Three main problems may be identified in this procedure:
1) DP design is normally done considering all limiting environmental condition aligned (or at least, waves and winds aligned). However, in a real condition, extreme waves, winds and currents may be not aligned, and the DP System may be able to counteract the resultant force. However, in the procedure explained before, it is a priori considered that the DP system will not be able to keep position in such a condition (limiting but not aligned), and the downtime is the over-estimated;

2) if the DP design has been done by a static procedure, the dynamic margin may have been under or over estimated. In the same way, the downtime evaluation considering the naive procedure will result a under or overestimated result;

3) maximum excursion or other limiting parameter of a DP operation (such as hawser tension) cannot be considered by this approach.

So, a procedure based on exhaustive dynamic simulations was developed for evaluating the downtime. The metocean data is used to generate a representative set of environmental conditions and its occurrence. After simulating, the vessel excursion, hawser tension and other operational parameters are evaluated for each case, and the occurrence of unsafe conditions may be properly evaluated. Comparisons between the downtime estimated by both procedures indicate that the naive procedure may lead to inaccurate results.

The following table presents the comparative results for DP and non-DP ST, as well as for Turret or Spread Moored FPSO in Campos Basin (Tannuri et al, 2009; Cueva et al., 2009). For a turret moored FPSO, the downtime is small, since the whole system (FPSO+ST) are free to weathervane. The advantages of the utilization of DP systems get more evident for the Spread Moored System.

<table>
<thead>
<tr>
<th>FPSO</th>
<th>DPST</th>
<th>Non-DPST</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downtime</td>
<td>Downtime</td>
<td>Downtime</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>days/year</td>
<td>%</td>
</tr>
<tr>
<td>Turret</td>
<td>1.8 to 2.4</td>
<td>7 to 9</td>
<td>2.4 to 3.0</td>
</tr>
<tr>
<td>Spread Moored</td>
<td>4.4 to 12.1</td>
<td>16 to 44</td>
<td>18.5 to 26.3</td>
</tr>
</tbody>
</table>

5. MODEL SCALE DP TESTS IN BRAZILIAN OCEAN TANKS

More recently, due to this increasing industry demand PETROBRAS has supported a project to improve technology in Brazilian laboratories to perform tests with DP-ST in the ocean basin. The overall purpose is to design and assemble most of the electromechanics, electronic components and control software of the scale model in the country as well as define the topology of the experimental facilities. The project is jointly conducted by University São Paulo and Federal University of Rio de Janeiro (Morishita et al, 2009). Fig. 14 shows the scale model during the tests at University of São Paulo controlled through the console that emulates a real DP one.

A preliminary experiment of a failure consequence analysis is shown in Fig. 15. A wind is acting against vessel bow, and a failure in bow thruster is imposed at t=730s. A large lateral deviation from the set-point can be verified. At t=980s, the bow thruster is restored. However, due to the angle deviation and the wind incidence, the vessel cannot return to its position. The thrusters do not have enough power to act against the wind. The wind is then turned off (at t=990s) and the set-point position is recovered.
Fig. 14. (left) Photos of a DP test at USP model basin and models of the tunnel and the azimuth thrusters (right) screenshots of uses interface.

Fig. 15. (left) deviation from set-point; (middle) thrusts; (right) pictures of the trial.
6. HYDRODYNAMIC AND AERODYNAMIC INTERACTION BETWEEN FPSO AND ST

The effects of hydrodynamic and aerodynamic interactions on a typical shuttle tanker, when offloading a FPSO moored in either a Turret or a SMS configuration are being studied by means of CFD and small scale experiments. The numerical models are then incorporated in the simulators and are used to evaluate the impact of such effects on the dynamics of the ST and on the DP System power requirement.

Such effects are not normally considered in the design of the tankers DP System, and the results of the analysis have showed that they are quite significant. In the present section, main conclusions of the studies are summarized, for current, waves and wind interaction. Based on the illustrative results presented, it should then be stressed that, when dealing with offloading operations of FPSOs in Spread Mooring configuration, special care should be taken concerning the strong interference effects that may arise from the vessel’s inability to weathervane. In this case, a time-domain simulation code that is able to predict the main contributions of wake effects in current, waves and wind forces, may significantly improve the reliability of the dynamic analysis of the multi-body system and a more accurate DP dimensioning may be achieved.

6.1 Current

In Illuminatti et al. (2009), the influence of current wake effects on the shuttle tanker station-keeping characteristics during offloading operations of a FPSO in Spread Mooring System configuration has been evaluated, adopting a typical Suezmax DP shuttle tanker as a case study. A semi-empirical model for the current force acting on the ST behind the FPSO has been derived and validated using small-scale experiment.

During the connection and oil transfer operation under common environmental condition (U=1.0 m/s), it was shown that hydrodynamic interaction effects in the current forces may increase the required power for the bow thrusters of up to 5.3%. This is indeed noteworthy, since it should be observed that DP power requirements are usually established by means of static analysis with simple hydrodynamic models, including 20% of extra power to compensate for dynamic and non-modeled effects. Furthermore, simulations of extreme conditions (U=2.0 m/s) indicated that the disturbances in the current field may increase the power demand up to 21% of bow installed power and 9.3% for the stern power.

Fig. 16 shows an illustrative result, with a full-loaded FPSO with 22.5° incident current direction. The color-map indicates the wake zone, since the color intensity is proportional to the current velocity. The required thrust to keep the ST inside the operational sector in a 15° or 30° relative angle are also shown, considering or not the wake effect. It can be noticed that the changes in mean flow direction in the bow part of the vessel acts against the bow thrust for the case of 30°, increasing the demanded power when the wake effect is considered. For a relative angle of 15°, an opposite effect is verified.

![Fig. 16. (left) ST inside the Operational Sector (Green zone); (right) two ST positions, and the mean thrusts considering or not the wake interaction effect](image-url)
6.2 Wave

In Queiroz Filho and Tannuri (2009), simulations of a real offloading operation were presented, considering or not the wave interference effect between the FPSO and the DP-ST. The Wamit potential analysis software was integrated to the simulator in order to update the drift coefficients during the simulation, as the relative position between the vessels significantly changes.

The results indicated that the wave interference effect normally reduces the DP power demand if the shuttle tanker is kept inside the operational sector. In this case, conventional simulations (that does not take into account such effect), over estimates the DP power. Considering a wave with 3.0m significant height, those differences may represent up to 30% of total DP power of a typical DP ST. However, there are some zones around the FPSO that the diffraction and irradiation effects increase the wave field close to the ST, representing up to 8.6% of the total DP power. In those cases, the DP power required to keep position is larger when compared to the simulations without shielding effect. In this case, conventional simulations (that does not take into account such effect), under estimates the DP power.

Fig. 17 shows two illustrative situations. For 210° incidence, the ST lies inside the shadow zone (see (c)) and the power required to keep in position is reduced, if the simulation considers the interference effect. For a 270° incidence angle, a different situation occurs, and the wave field close to the ST is larger due to the presence of the FPSO. The DP power increased due to the wave interference effect. A more comprehensive study considering different loading conditions, relative positioning and realistic wave height/periods in Campos Basin are still being conducted.

![Fig. 17. (a) System configuration; (b) DP total power for 210° and 240° wave incidence; (c) Wave field for a regular wave, with 1m height, 210° direction and 7s period; (d) Wave field for a regular wave, with 1m height, 270° direction and 5s period](image-url)

6.3 Wind

A simplified system is being considered for a preliminary analysis of wind interference between FPSO and ST as indicated in Fig. 18. CFD calculation is used, calibrated with wind tunnel measurements of a similar system.

Fig. 19 shows the lateral and longitudinal wind coefficients, and a large difference is verified considering or not the presence of the FPSO. This wind interference effect will cause important differences in the DP power estimation. Such study is still being executed.
7. CONCLUSIONS

In this paper, several aspects regarding DP assisted offloading operations in Brazilian Waters were discussed. The main focus was to present the regulatory guidelines and the new tools and procedures that are being developed by a continuous industry-university cooperation program.

8. ACKNOWLEDGMENTS

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9. REFERENCES


APPENDIX. THE TPN OFFSHORE SIMULATION SYSTEM

The Numerical Offshore Tank (TPN-USP) is a time domain numerical procedure designed for the analysis of moored and DP offshore systems. The inputs of the simulator are:

- Floating body main parameters (dimensions, mass matrix, etc.);
- Aerodynamic drag coefficients (following standard given by OCIMF, 1994);
- Current coefficients (following standard given by OCIMF, 1994) or hydrodynamic derivatives;
- Hydrodynamic coefficients (potential damping, added mass, first and second order wave force coefficients);
- Environmental conditions (wave and wind spectra, current);
- Mooring and risers system characteristics;
Thrusters characteristics and layout;
DP modes and parameters.

The non-linear time-domain simulation runs in a parallel processing computer cluster and outputs time series describing the motions of the floating units in six degrees of freedom (6dof), tensions on the mooring lines and hawser, propellers thrust and power, etc., and a corresponding statistical summary. 3D-stereo visualization outputs are also available (Fig. 20).

A.1 SHIP DYNAMICS AND ENVIRONMENTAL ACTION MODELING

For the purpose of evaluating the DP system, only the horizontal motions of the ship must be considered and the mathematical model can be built by applying mechanical laws. The low-frequency motion of the system can be conveniently expressed in two orthogonal reference systems, one being the Earth-fixed (OXYZ) and the other (Gx1x2x3) a non-inertial reference frame fixed on the vessel (see Figure 3). The origin of this reference frame is the intersection of the midship section with the longitudinal plane of symmetry of the ship, and it is taken as the center of gravity (G). Additionally, the axes of reference frame are taken to be coincident with the principal axes of inertia of the vessel. Bearing in mind these assumptions, the resulting equations of low-frequency motions are:

\[
\begin{align*}
(M + M_{11}) \ddot{x}_1 + (M + M_{22}) \ddot{x}_2 + M_{26} \ddot{x}_6 + C_{11} \dddot{x}_4 + F_{1EH} + F_{1T} &= 0; \\
(M + M_{22}) \ddot{x}_2 + M_{26} \ddot{x}_6 + (M + M_{11}) \ddot{x}_1 + C_{22} \dddot{x}_2 + F_{2EH} + F_{2T} &= 0; \\
(I_Z + M_{66}) \ddot{x}_6 + M_{26} \ddot{x}_2 + M_{26} \ddot{x}_1 + C_{66} \dddot{x}_6 + F_{6EH} + F_{6T} &= 0.
\end{align*}
\]

where \( I_Z \) is the moment of inertia about the vertical axis; \( M \) is the mass of the vessel, \( C_\gamma \) are damping coefficients, \( M_\delta \) are added mass terms, \( F_{1EH}, F_{2EH}, F_{6EH} \) are surge, sway and yaw environmental (current, wind and waves) and hawser forces, \( F_{1T}, F_{2T}, F_{6T} \) are forces and moment delivered by the propulsion system. The variables \( \ddot{x}_i \) are surge and sway low-frequency velocities and \( \dddot{x}_i \) is the yaw rate.

The position and heading of the vessel related to the Earth-fixed coordinate system are obtained from the following equation:
A.2 DP ALGORITHMS AND PROPELLER MODEL

Usually, three main classes of algorithms are used in commercial DP systems. A low-pass filter, called wave-filter, separates wave-frequency components from the measured signals. Such decomposition is mandatory, as the DP system is able to control only low-frequency motions. High-frequency motion control would require an enormous power and could cause extra tear and wear in propellers. Normally, an Extended Kalman Filter is used to perform such a task.

Furthermore, a thrust allocation logic (TAL) has to be used to distribute control forces to the thruster system. This algorithm guarantees minimum power consumption, generating the required total forces and moment to keep the vessel position.

At last, a control algorithm uses filtered motion measurements to calculate such required thrusts. Commercial DP Systems use a Proportional-Derivative (PD) controller, coupled to a wind feed-forward term. Such a term enables one to estimate the wind load action on the vessel (based on wind sensor measurements), thus compensating it by means of the action of propellers.

The simulator includes models for controllable pitch propellers (cpp) and for fixed pitch propellers (fpp). The model takes into account their characteristic curves, and is able to estimate real power consumption and delivered thrust. For fpp propellers, dynamics of rotating parts are also simulated, accounting for the delay between the control command and the propeller response due to the inertia of the system. Furthermore, for cpp propellers, a maximum pitch variation rate is defined in order to simulate the governing mechanism that is responsible for the pitch variation. A detailed description of DP algorithms included in the numerical simulator can be found in Tannuri and Morishita (2006).