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OIL TRANSFER BETWEEN DP SHUTTLE AND CONVENTIONAL TANKERS IN TANDEM CONFIGURATION: A NUMERICAL EVALUATION OF ALTERNATIVES

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ABSTRACT

The recent Pre-Salt oil fields discovered in Brazil are imposing some new logistical challenges concerning distribution in the internal and external markets. In order to reduce the demand in the on-shore terminals, the export oil could be directly transferred from the platforms to the export tankers. However, internal regulations define that the offloading operation must be carried out by DP Shuttle Tankers (ST). Due to this definition, since 1994, the DP-ST fleet has been increased, and the safety and uptime of the offloading operations are improving. The utilization of a DP-ST to navigate across the oceans for exportation is not economically advantageous, since the day-rates of those vessels are significantly higher than conventional (non-DP) STs. Hence, a possible solution is to transfer the oil from the DP-ST to the conventional ST in the offshore waters. Several alternatives were proposed, considering stationary tandem configuration, ship-to-ship or tandem with advance speed.

This paper is focused on the stationary tandem configurations, considering the aid of offshore tugboats and/or monobuoys. The alternatives comprehend the conventional ST connected to the DP-ST or vice-versa, with the position being held by the DP system, a tugboat or a monobuoy. The numerical time-domain simulations were used for predicting the safety under typical environmental conditions, with crossed-bimodal sea states and sudden wave-wind changes. The relative motions of the vessels, hawser force, DP or tugboat utilization and loads on the vessels mooring equipment were verified in order to define the limiting environmental window for a safe operation, for each one of the alternatives. This comparative analysis was used to support the decision about this topic, since the advantages and problems of each solution could be identified.

KEYWORDS

Oil transfer, DP system, Offshore operation, Tandem configuration

INTRODUCTION

Petrobras Transporte S.A. – Transpetro is a Brazilian logistics and fuel transportation company, with 28 waterway offloading terminals covering 8,698 kilometers of the Brazilian coastline. They are operated by means of piers, mono-buoys or buoy frames. The sudden increase of the oil exploration in Brazilian offshore fields demands a quite expressive improvement in the whole distribution chain, mainly considering the offloading terminals. Besides the investments in infra-structure that are being made by the company, this logistic constraint can be reduced if the export oil could be avoided to come to shore, being directly transferred from the platform to the export tanker. However, the oil can only be offloaded from the FPSOs by DP-Shuttle Tankers, due to the company safety regulations [12].

The utilization of a DP-ST for long course navigation is not economically advantageous, since the day-rates of those vessels are significantly higher than conventional (non-DP) STs. Hence, a possible solution is to transfer the oil from the DP-ST to the conventional ST in the offshore waters, close to the oil fields. Several technical problems may arise from this kind of operation. The environmental conditions in the Brazilian offshore field are quite particular, with frequent bimodal sea states (local waves come from a specific direction and the swell comes in a 90º direction). Furthermore, incidence inversions are also observed and are associated with cold weather.

Several alternatives comprehend tandem stationary configuration, and are the focus of the present paper. The conventional ST is connected to the DP-ST or vice-versa, with the position being held by the DP system, a tugboat or a monobuoy. The critical environmental conditions are used, and a full time domain computational simulator is used to estimate vessel motions, hawser tension and DP utilization during the operation. Operational criteria adopted by Petrobras/Transpetro were then used to verify the risks associated to each operation and the technical viability. This analysis was used to support the decision about possible alternatives for offshore oil transfer, since the advantages and problems of each solution could be identified.

Tandem operations may present very complex and rich dynamic responses, since 2 or 3 bodies are connected by elastic constraints (hawsers and mooring lines). Furthermore, hydro/aerodynamic interaction is important, due to the small distance between the vessels. Scientific and industrial community effort for developing and validating numerical models for tandem operations is then justified, as for example [3], [4], [6], [14].

SIMULATOR AND NUMERICAL MODEL DESCRIPTION

The availability of the proposed arrangements of the vessels is judged by verifying the dynamics of the floating bodies under the action of the environmental forces and moments. The important parameters are the relative positions, the tension in the hawser and total DP thrust. Those tasks are performed through Dynasim numerical code [7].

The ships are considered as rigid bodies and their dynamics are represented by a 6 DOF Newtonian equation and their corresponding kinematics equations.

The ships can present mooring, risers and hawser lines. They are represented by a quasi-static model based on the catenary equation.

The current force mode used in the present simulations is based in the Cross flow Model based on Obokata [8] with constant current profile.

Wind forces acting on the ship hull are modelled using traditional drag force formulation whose coefficients are based on model tests or OCIMF experimental curves [9]. The simulator allows constant or gusty wind. The wind spectra implemented in the code are Harris, Wills, API, NPD, etc.

JONSWAP sea spectrum formulation is used to characterize the sea state. Directional spreading can be considered by the cos2s formulation. Bimodal sea-states are simulated as a sum of two generic directional wave components.

The high frequency motion (HF) due to the wave action are computed by imposing the wave 1st order forces to the body. All motion components (6 dof) are obtained dynamically solving the equations of motion. This approach, although more time consuming than the traditional RAO method, provides more accurate results, since the body motions are calculated including all external forces, and not simply imposing HF motions adding RAO. This is important when the vessel is subjected to HF external forces other than waves, such as hawser forces.

Wave second-order effects are calculated using the QTF approximation proposed by Aranha and Fernandes [2]. Wave-drift damping effects are modeled following [1]. The wave coefficients are imported by any commercial code for wave analysis (such as Wamit, Acqwa or Hydrostar).

Three main classes of algorithms are used in a commercial DP system: wave filter, thrust allocation algorithm and control logic. The Dynasim includes the DP algorithms that are typically used in modern commercial systems, in order to address the performance of real DP ships (more details are presented in [13]):

- Wave Filter: The wave-filter is employed to separate wave-frequency components from measured signals. Such decomposition must be performed because the DP system must only control low-frequency motion, since wave-frequency motion would require enormous power to be attenuated and could cause extra tear and wear in propellers. An Extended Kalman Filter (EKF) is used, which incorporates a model of the system. In the EKF, the vessel motion is regarded as the sum of two linearly independent response functions. A low frequency model yields motions due to maneuvering forces and environmental forces due to wind, current and wave drift, and a high frequency model yields vessel response due to waves.
- Control logic: it uses the filtered motion measurements to calculate the required total forces and moment to keep the vessel close to the desired position and heading. A conventional 3-axis uncoupled PID (Proportional, Integral, Derivative) controller is used, coupled to a feedforward wind compensator. Control gains are automatically evaluated using pole-placement technique.
- Thrust allocation algorithm: it is an optimization algorithm used to distribute control forces among thrusters. It guarantees minimum power consumption to generate the required total forces and moment required by the controller. A pseudo-inverse matrix technique was implemented, with extra features that are normally employed in real DP Systems, such as azimuth angle dead zone control, re-allocation in case of saturation and attenuation filters.

Furthermore, the simulator includes models for cpp (controllable pitch propeller) and fpp (fixed pitch propeller) propellers, taking into account their characteristic curves, being able to estimate real power consumption and delivered thrust. It also evaluates time delay between command and propeller response, caused by axis inertia (in case of fpp propellers). Thruster-current interaction is considered, but the other interaction effects (thruster-hull and thruster-thruster) are not considered in the present version of the simulator.

VESSELS DESCRIPTION

The oil is transferred from the DP Vessel to the Conventional Shuttle Tanker, and the typical characteristics of both vessels are presented in this section. All simulations considered two loading conditions:

- Initial stage of the operation: DP Tanker fully loaded and Conventional Shuttle Tanker ballasted;

- Final stage of the operation: DP Tanker ballasted and Conventional Shuttle Tanker fully loaded.

SHUTTLE TANKER (CONVENTIONAL-TANKER)

The shuttle tanker considered in this project is a conventional (non-DP) VLCC in two different loading conditions: ballasted or full. The main properties are shown in Table 1

Table 1 - Shuttle tanker geometrical properties

	Loaded	Ballasted
Length Overall LOA (m)	337.3	
Length between perp. L_{BP} (m)	320.0	
Beam (m)	54.5	
Depth (m)	27.0	
Draft (m)	27.0	9.0
Displacement (ton)	310720	127510

DP VESSEL (DP-TANKER)

Two Suezmax DP-Shuttle Tankers are considered in the analysis, with different DP layouts. The main characteristics of the vessels are indicated in Table 2.

Table 2 - DP vessel geometrical properties

	Loaded	Ballasted
Length Overall LOA (m)	269	
Length between perp. L_{BP} (m)	258	
Beam (m)	46	
Depth (m)	24,4	
Draft (m)	17.5	8.0
Displacement (ton)	175170	75694

The ST1 is a DP-2 vessel with 8MW total DP power, a typical configuration of vessels that operate in the Campos basin for spread-moored FPSOs offloading operation (Table 3). The ST-2 is also a DP-2 vessel, with an extra bow azimuth thruster (10.2MW total DP power), and is also intended to operate in the Santos basin (Table 4).

Table 3 - ST1 DP layout

Propeller	Position relative to the midship	Maximum thrust	Total Power
1 - Tunnel Thruster Bow	x = 128m, y - 0m	± 29 tonf	2200kW
2 - Azimuth Thruster Bow	x = 123m, y - 0m	+40 tonf; -20 tonf	2200kW
3 - Azimuth Thruster Stern	x = -79m, y - 0m	+40 tonf; -20 tonf	2200kW
4 - Tunnel Thruster Stern	x = -114m, y - 0m	± 18 tonf	1400kW
5 - Main Propeller	x = -125m, y - 0m	+206 tonf; -120 tonf	16860kW

Table 4 - ST2 DP layout

Propeller	Position relative to the midship	Maximum thrust	Total Power
1 - Tunnel Thruster Bow	x = 128m, y - 0m	± 29 tonf	2200kW
2 - Azimuth Thruster Bow	x = 123m, y - 0m	+40 tonf; -20 tonf	2200kW
3 - Azimuth Thruster Bow	x = 114m, y - 0m	+40 tonf; -20 tonf	2200kW
4 - Azimuth Thruster Stern	x = -79m, y - 0m	+40 tonf; -20 tonf	2200kW
5 - Tunnel Thruster Stern	x = -114m, y - 0m	± 18 tonf	1400kW
6 - Main Propeller	x = -125m, y - 0m	+206 tonf; -120 tonf	16860kW

DESCRIPTION OF ALTERNATIVES FOR OIL-TRANSFER

Five different arrangements were simulated with different combinations of the bodies (Shuttle tanker, DP vessel, Monobuoy, Tugboat). The models are described in the present section.

An important comment about the shielding effect must be presented. Wind ([6], [15]), wave ([10],[11]) and current ([5]) shielding effects may influence the dynamics and DP performance in tandem offloading operations. However, those effects require additional efforts to be considered in a time-domain simulation model. CFD analysis, experimental velocity field measurements and integration with potential wave software are required for a proper calculation of shielding effects. The purpose of the present paper is to make a comparative analysis between tandem solutions and to identify major dangers and operational difficulties. Also, assuming that shielding effects do not qualitatively change the dynamics of the system, those effects were not considered in the present paper.

Some other modeling simplifications adopted in the numerical model are described in each section below.

DP VESSEL - SHUTTLE TANKER - TUGBOAT

In this configuration, the DP Vessel keeps the position using the DP system while the Shuttle Tanker, without any active propulsion, is connected to it by means of a hawser. A tugboat is used to reduce the occurrence of fishtailing motion and to keep a safe distance between the vessels (Figure 1). The tugboat was simulated as a constant force parallel to the shuttle tanker.

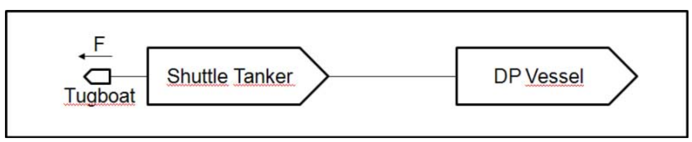

Figure 1 - Configuration 1

TUGBOAT - SHUTTLE TANKER - DP VESSEL

In this configuration, the Shuttle Tanker is connected to the tugboat, which uses its DP-System for stationkeeping. The DP Vessel then connects to the Shuttle Tanker using the relative-DP system to keep the distance (Figure 2). Hawser is used only for safety issues, but it is slackened during the operation. For the sake of simplification, the tugboat was modeled as a fixed-point in this analysis.

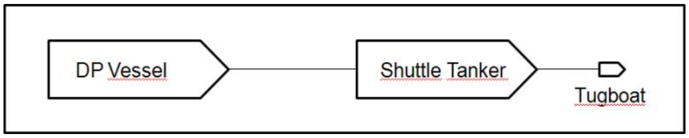

Figure 2 - Configuration 2

MONOBUOY - SHUTTLE TANKER - DP VESSEL

In this configuration, the shuttle tanker is connected to a monobuoy moored to the seabed. The DP Vessel then connects to the Shuttle Tanker using the relative-DP system to keep the distance (Figure 3). Hawser is also slackened during the operation. Again, the tugboat was modeled as a fixed-point, and actually Configurations 2 and 3 are the same simulation models.

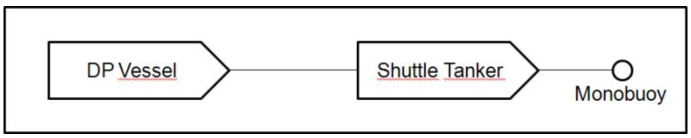

Figure 3 - Configuration 3

MONOBUOY - SHUTTLE TANKER - DP VESSEL - TUGBOAT

In this configuration, similar to the previous one, the shuttle tanker is connected to a monobuoy moored to the seabed. The DP vessel is connected to the Shuttle Tanker stern, but the DP system is turned off. A tugboat is used to reduce the occurrence of fishtailing motion and to keep a safe distance between the vessels (Figure 4). Hence, no relative positioning device is necessary for this operation, which may be an advantage as compared to Configuration 3. However, the stern mooring point of conventional Shuttle Tankers is designed to support up to 46tons, and it may restrain this kind of operation.

The monobuoy was simulated as a fixed point and the tugboat was simulated as a constant force, parallel to the DP vessel.

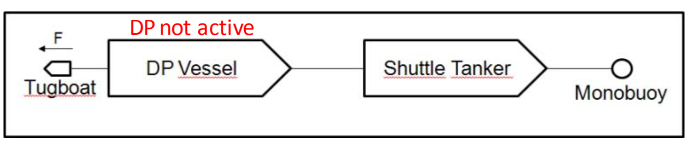

Figure 4 - Configuration 4

MONOBUOY - DP VESSEL - SHUTTLE TANKER - TUBGOAT

In this configuration, similar to the previous one, the DP vessel is connected to a monobuoy moored to the seabed. The DP system is not enabled. The Shuttle Tanker is connected at the DP vessel's stern and a tugboat is also used for keeping the relative position, as seen in Figure 5. Compared to the previous configuration, this solution has the advantage that the stern mooring point of new DP Vessels can support up to 100tf.

The monobuoy was simulated as a fixed point in space connected with a mooring line to the shuttle tanker. The tugboat was simulated as a constant force, parallel to the DP vessel.

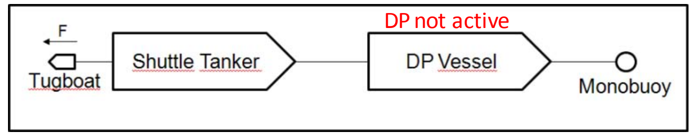

Figure 5 - Configuration 5

ENVIRONMENTAL CONDITIONS

Typical environmental conditions in Brazilian oil fields were considered in the simulations (Figure 6).

For all the conditions, current direction is defined as South (goes to) and the speed is defined as 1.0m/s. This direction is the most representative in the Campos basin, since 80% of a long-term register indicates the SE-S-SW direction. Furthermore, the adopted speed is an upper limit, since 98% of the registers indicate current speeds below 1.0m/s.

Wave period (Tp=8s) and significant height (Hs=3.5m) and wind speed (20m/s) are adopted as the upper limit accepted for offloading operation [12]. Two typical directions (coming from) are considered: NE (condition A) and SE (condition B).

During more than 40% of the time, bimodal sea-states are verified in Brazilian fields. This corresponds to a swell component normally coming from S-SE, associated with the local sea. So, an additional condition is considered (condition C), with a swell (Tp=14s; Hs=4m) associated with NE local sea. Finally, sudden variation of wind-wave direction is also common, during storm or incursions of cold air masses. This condition was also simulated (condition D), considering the variation from NE to SE for 2hours.

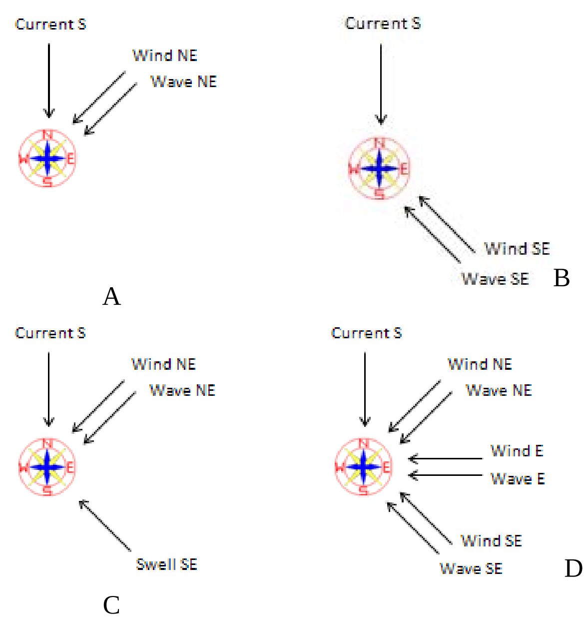

Figure 6 - Environmental conditions

RESULTS

In this section, the results from the simulation of all configurations under different conditions will be presented. Some general conclusions are based on the simulation results, illustrated for some specific conditions. The results were presented and discussed with DP captains that participated in the judgment and selection of the best options. The main criteria used by them for evaluating each solution are:

- hawser tension must be smaller than 100tons
- DP mean utilization must be smaller than 80%
- vessels drift must be at acceptable levels
- personal experience about operational difficulties and risks

RESULTS – CONFIGURATION 1

Figure 7 shows the simulation results for environmental condition A, under a reduced current speed (0.7m/s), wave height (2m) and wind speed (12m/s). The figure shows the trace-plots of the position of the vessels and the mean utilization of DP thrust, considering ST2 DP layout. For this milder environmental condition, the vessels can keep position, but the DP utilization is excessive (larger than 80% for some thrusters). This is not acceptable during long operations, accepting up to 80% utilization. The weathervane DP mode is used, with the control point located at the bow of the vessel.

The DP Vessel is designed to keep its own position under typical environmental conditions, and in the present configuration, the DP System is required to keep the position of the VLCC, that is obviously quite demanding.

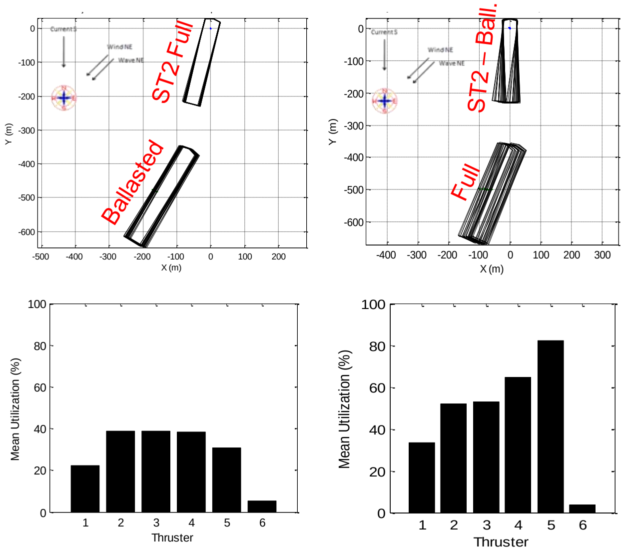

Figure 7 - ST2; Configuration 1; Reduced Env. Cond. A

Simulation results under the nominal intensities of the environmental conditions presented in section 4 indicated the system cannot keep position, even with DP utilization larger than 80%.

Static capability analysis can be used to underline that this configuration requires excessive DP utilization. Figure 8 presents the power utilization capability plots for the ST2-Ballast vessel. For the Reduced Environmental Condition A (left), the power utilization of the most demanded thruster reaches 80% when the wave-wind incidence is 45^o, confirming the results obtained in the dynamic analysis (Figure 7). For the nominal condition (right), the vessel cannot keep position for this incidence, requiring 170% of the nominal thruster power.

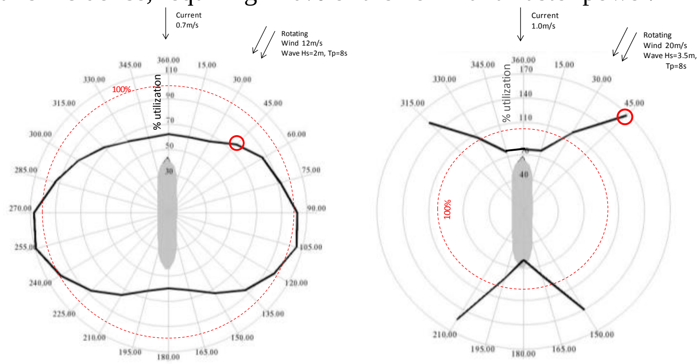

Figure 8 - ST2; Capability plots; (left) Reduced Env. Cond. A; (Right) Env. Cond. A

RESULTS – CONFIGURATION 2 & 3

Since the modeling for configurations 2 and 3 was the same (fixed point at the origin to simulate both the monobuoy or the tugboat), the results will be shown together. The same conclusions could be drawn, considering this level of modeling simplification.

Figure 9 shows the results for the DP-ST2 under the nominal environmental condition A. The vessels can keep a safe distance (120m) during the whole operation, with variation smaller than 10m and no hawser tension. For the full loaded DP-Vessel (initial stage of the operation), the DP utilization is quite larger, reaching up to 80% for the bow-azimuth thrusters (# 2 and #3). The high value of current speed (1.0m/s) can explain this observation.

A 120m-length hawser is used to connect the vessels. It is kept slackened and no traction was observed during the simulations, since the DP could keep the relative distance (100m). Of course, this operation is carried out under a relative DP mode, requiring relative positioning devices.

Figure 10 shows the results for environmental condition D (wave-wind direction variation). It can be seen that the DP-ST can keep the relative distance and no dangerous situation was observed.

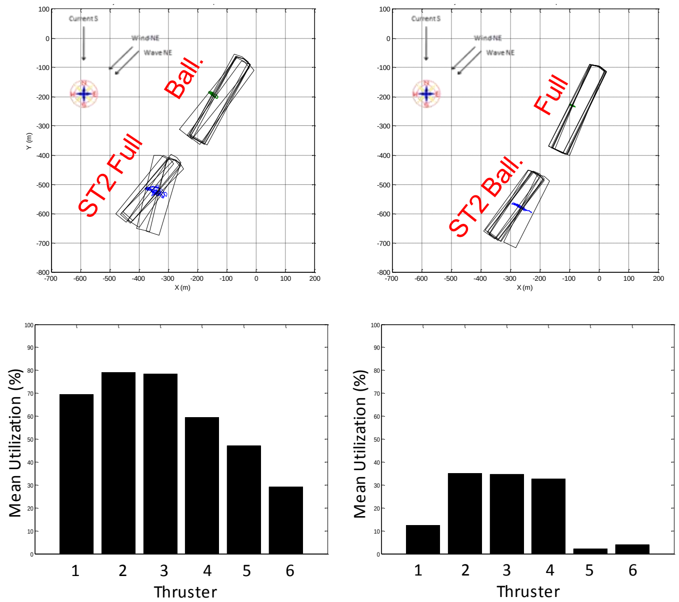

Figure 9 - ST2; Configuration 2/3; Env. Cond. A

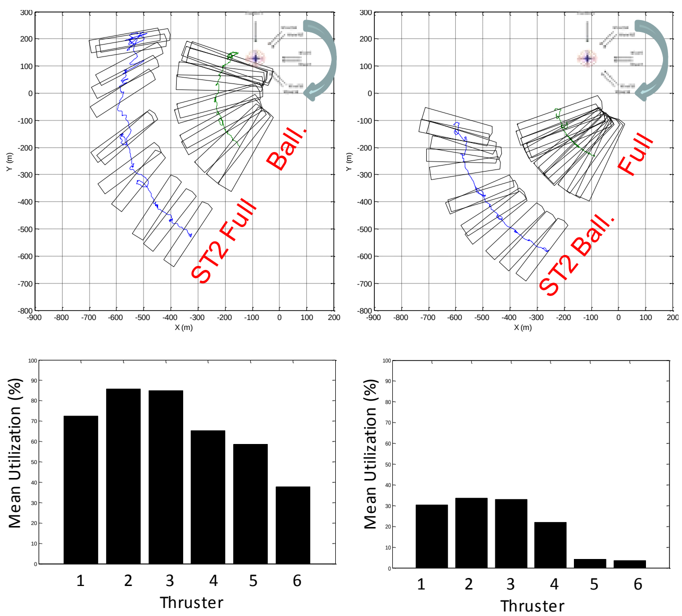

Figure 10 - ST2; Configuration 2/3; Env. Cond. D

The simulations of ST1 indicated that the DP mean utilization reached up to 90%, which was expected since it has only one bow-azimuth thruster.

Therefore, the simulations indicated that configurations 2&3 are viable, especially for the ST2 DP Vessel, which could maintain its position for all conditions and loadings under a mean utilization smaller than 80%.

Configuration 2 has the drawback of requiring an offshore 140tons DP tug-boat, that is a quite scarce resource. However, it has the advantage of requiring no infra-structure such as a moored monobuoy.

For both solutions (2&3), a relative positioning system has to be used, and the conventional tanker must be adapted to it. In some cases, one operator from the DP vessel will have to board the tanker to conduct the installation of the system (an optical or ultrasonic target for example).

RESULTS – CONFIGURATION 4

Figure 11 shows the simulation results for environmental condition B. In this case, the DP is not enabled, and the utilization bar-graph was then omitted, and was replaced by a graph showing the tension of the hawser that connects the vessels. A tugboat is connected to the stern of the ST, and is modeled as a constant 30tons tug force.

The simulations indicated that the hawser force reaches up to 210tons, which is not acceptable. The conventional Shuttle Tankers are equipped with stern bollards that can withstand up to 46tons. It thus reduces the environmental window that can be safely considered for the operation.

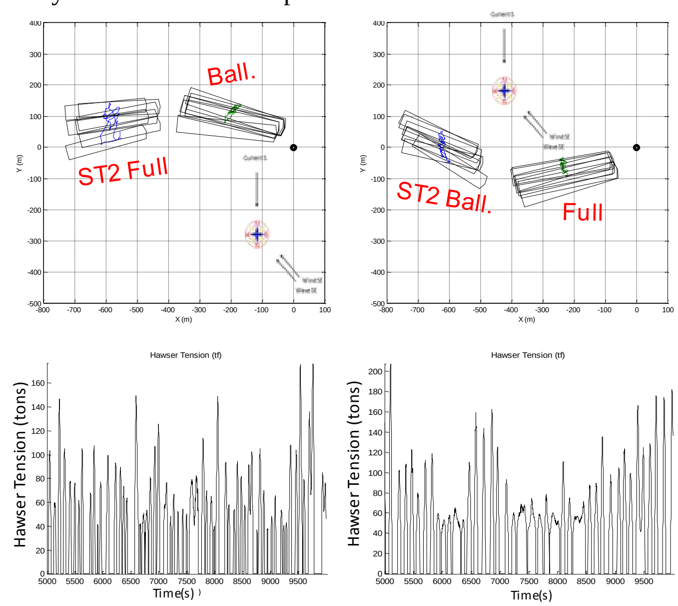

Figure 11 - Configuration 4; Env. Cond. B

RESULTS – CONFIGURATION 5

DP Shuttle Tankers are equipped with 100tf stern winches, and so the positions of the vessels are swapped from the previous configuration.

For the nominal environmental conditions, the hawser tension also exceeds 100tons, as indicated in Figure 12. Hence, simulations were carried out with the same current speed, but with milder winds and waves. For the SW incidence, for example, the hawser tension is kept smaller than 100tons for Hs=1.8m wave height and 10m/s wind speed. This was the critical case considering the four simulated environmental conditions.

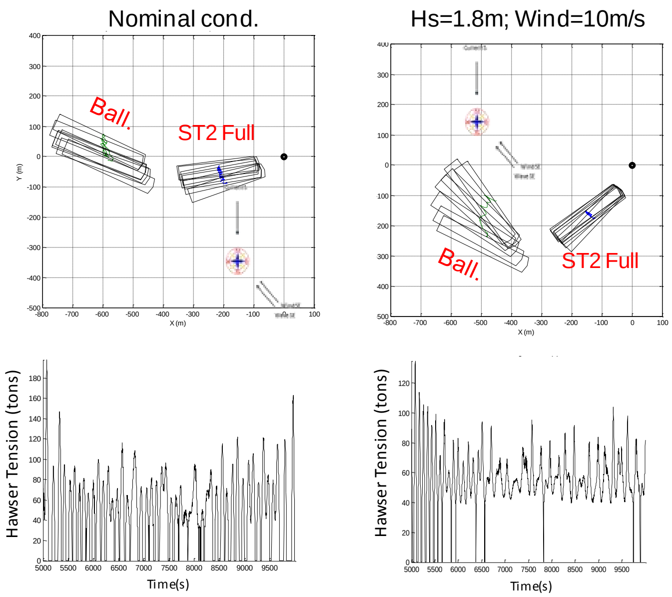

Figure 12 - Configuration 5; Env. Cond. B

CONCLUSIONS

This paper presented the numerical modeling and simulation of five different alternatives for offshore oil transfer between vessels. Configurations 2, 3 and 5 showed to be feasible in terms of hawser tension, tug force and DP mean utilization, considering the typical environmental conditions evaluated herein.

However, a broader analysis of the results indicated that the installation of a monobuoy is in fact a better solution, avoiding the need of using a 140tons DP offshore tugboat during the entire operation (as required in configuration 2).

Thus, with the monobuoy deployed, both configuration 3 and 5 can be used. If relative DP equipment is available in the stern, part of the conventional tanker, configuration 3, can be used. Otherwise, a smaller tug-boat can be used and configuration 5 is adopted.

The next step of the research is to perform a more complete numerical model of solutions 3 and 5 (considering the actual model of the monobuoy and the tugboat), and to perform experiments in an oceanic basin.

A parametric analysis of DP parameters must also be done, in order to verify if the spring stiffness introduced by the hawser is affecting the closed loop performance, and if is inducing longitudinal oscillations and large hawser peak forces. Waals [16] showed this possible effect in a similar system.

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