Hydrodynamic Research on and Optimizing Dynamic Positioning System of a Deep Water Drilling Vessel

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Abstract

Computer simulations and model tests have been used to design and optimize the hydrodynamic performance of a Deep Water Drilling Vessel operating under full DP. The paper describes the procedure used to investigate the thruster-hull and thruster-thruster interaction and the automatic closed loop control system as used for the computer simulations and model tests. Results of the thruster interaction investigation will be shown. Results of the computer simulations on the DP heading capabilities in various design operating weather conditions will be presented and compared with the results of the model tests.

Introduction

The deep water drilling vessel is a fully dynamic positioned large displacement monohull. The vessel is designed for drilling operations in water depths up to 10,000 ft. Investigations were focussed on the design storm conditions in the Gulf of Mexico and potential operations West of Shetland.

In the design stage of the vessel hydrodynamic research was applied to the vessel. Besides theoretical and experimental investigations on the dynamic positioning system also research was carried out on the prediction of the speed of the vessel. The total research program therefore can be split in the following parts.

Tests in the Deep Water Towing Tank. The main reason for the tests was to predict the service speed of the vessel. For this purpose a model of the vessel provided with 6 azimuthing stock thrusters on a scale 1:26.81 as used and the following tests were carried out:

- propeller open water characteristics,
- resistance tests for the scantling draft \((T = 13.00 \, m)\) with open moonpool,
- resistance tests for the transit draft \((T_F = 7.97 \, m; T_A = 8.97 \, m)\) with open and closed moonpool,
- propulsion tests for the transit and scantling draft with open moonpool.

From the results with the presented model equipped with the appendages and fitted with 6 KaMeWa thrusters the following speeds were predicted for the ship in service condition with a sea margin of 15 per cent:

- transit draft more than 14 knots,
- scantling draft more than 12 knots.

In addition to these tests preparation tests for the DP-system were carried out. The following tests were carried out:

- hull current loads with the ship in scantling draft;
- thruster-hull interaction in calm water;
- thruster-thruster interaction in calm water.

DP Computer Simulation Study. Prior to the DP tests a DP computer simulation study was carried out. The study was carried out with the DPSIM computer program, Ref. 1. The objectives of the DP study was to identify and optimize the DP controller settings incl. the thruster allocation algorithm for the DP capability of the vessel in various design storm conditions. Besides the particulars of the vessel also the wind, current and wave drift data and thruster particulars were necessary as input for the computer simulation study. The wind coefficients were derived from windtunnel tests, see Ref. 2. The current coefficients were derived from the towing tests and the wave heading dependent quadratic transfer functions of the wave drift forces/moments were computed with a 3-D diffraction program, see Ref. 3. The results in terms of DP controller settings and the thruster allocation algorithm were used as input for the DP model tests.

Tests in the Wave and Current Basin. The general purpose of the tests was to investigate the performance of the design of the DP system of the vessel in the various design weather conditions. Besides the performance of the DP system also the following design aspects were considered:

- roll decay,
- motions and accelerations,
• relative wave heights in the moonpool,
• greenwater and slamming loads on the vessel (hovering in North West Atlantic survival storm),
• thruster loads and angles.

For these purposes a model of the vessel provided with 6 azimuthing stock thrusters on a scale 1:55 was used.

Results of investigation of the thruster-hull and thruster-thruster interaction will be presented and discussed. The automatic closed loop control system as used for the computer simulations and model tests will be described. Results of the computer simulations on the DP heading capabilities in the different operating weather conditions will be presented and compared with the results of the model tests on the deep water drilling vessel.

Deep Water Drilling Vessel
The particulars of the drilling vessel are given in Table 1, while the general arrangement is given in Fig. 1.

The vessel was equipped with 6 azimuthing thrusters. The azimuthing thrusters are fixed pitch, variable speed and non reversible. The particulars of the propellers are given in Table 1. Each unit has a power of 4 MW. Of this power 94% is available to the propeller after deduction of the transmission losses. In order to reduce the thruster-hull interaction the nozzles to the thrusters were tilted 5 degrees.

The azimuthing speed of the thrusters is 100 RPM. The bollard pull per thruster with nozzle amounts to 760 kN.

During the DP tests for potential operation in the North West Atlantic the thrust saturation was increased to 1040 kN. This bollard pull force, however, corresponds with a propeller diameter of 4.3 m and an 5.8 MW unit.

Weather Conditions
For these purposes a model of the vessel provided with 6 azimuthing stock thrusters on a scale 1:55 was used.

As design weather conditions for the Gulf of Mexico the 10-year winter storm, loop current and sudden (wind) squall conditions were applied. The storm condition as determined for the North West Atlantic was more severe than the 10-year G.o.M. winter storm. The specific data are given in Table 3.

Thruster Interaction
Thruster-Hull Interaction. Thruster-hull interaction tests have been carried out to investigate the influence of the hull, the bilge keels, included, on the operating performance of the thrusters. All thrusters were instrumented (scale 1:26.81). Measured quantities are the components of the forces acting on the hull, the unit thrust, the thrust acting on the nozzle, the thrust on the propeller and the torque and rotation rate of the propeller. Theoretically the unit thrust corresponds with the sum of the thrust on the nozzle and the propeller. The forces acting on the hull were measured using the same mounting frame (6-components force transducer) as used during the current load measurements.

Tests were performed on some thrusters. A separate thruster is tested for a range of azimuth angles from 0° to 360° in steps of 15°. To evaluate the effects of the interaction the total measured forces acting on the hull have been compared to the measured unit thrust. The thrust loss percentage is defined by:

\[ \Delta T_{\text{loss}}(\%) = \frac{T_{\text{unit}} - F_{\text{hull}}}{T_{\text{unit}}} \]

As an example the thruster-hull interaction has been presented for thruster No. 5. The thruster-hull interaction has been measured with and without bilge keels. The results are given in Fig. 2. For the thruster numbering, see Fig. 1. The definition of the thrust angle is as follows: thrust 0° = forward thrust, thrust 90° = thrust to starboard, thrust 180° = backward thrust and thrust 270° = thrust to portside.

From the results in Fig. 2 it can be concluded that the thrust losses of thruster No. 5 are relatively small and that the influence of the bilge keels is very small and does not have to be accounted for in the thruster logic of the DP system.

Thruster-Thruster Interaction. Thruster-thruster interaction is the effect on the performance of a thruster influenced by the operation of an other nearby thruster. In this section 2 examples of thruster-thruster interaction will be given. In Fig. 3 the interaction between thruster No. 4 and No. 5 is given, while in Fig. 4 the interaction between thruster No. 1 and No. 2 is presented. For these tests the same model was used as for the thruster-hull interaction tests. The measured unit thrusts are shown in the Figs. 3 and 4.

In Fig. 3 thruster No. 5 is fixed in zero degrees direction. The propeller ran 160 RPM, while the measured thrust of the unit was 648 kN. Thruster No. 4 was turned by steps of 15°. The propeller runs 160 RPM also, while the measured thrust of the unit, in the zero-degree direction, amounted to 615 kN. As is shown the unit thrust No. 5 reaches a maximum reduction of about 15% at an angle of 23°. At this angle thruster No. 5 operates in the propeller race of thruster No. 4, which is almost straight into the nozzle of thruster No. 5. Therefore the propeller of thruster No. 5 operates at a higher intake velocity which is translated into a higher J-value (decrease of the angle of attack of the propeller blades), resulting in a reduction of the propeller blade loading.

In Fig. 4 thruster No. 1 is fixed in zero degrees direction. Thruster No. 2 was turned by steps of 15° from 270° to 360°. Both propellers ran 160 RPM. A different situation arises for thruster No. 1 operating in the propeller race of thruster No. 2. The unit thrust of thruster No. 1 increases for thruster angles ranging from 270° to 310° and reaching a maximum increase of 10% at 285°. In this situation thruster No. 1 operates in a flow field which is directed under a large incident angle with the direction of the nozzle. The cross-flow effectively reduces the J-value, at which the propeller operates, thereby increasing the loading of the propeller blades.

These two examples show typical effects of thruster-thruster interaction.
Computer Simulations

Description of Program. The DP computer simulation study was carried out with the DPSIM computer program. The DPSIM program is a time domain simulation program for dynamically positioning of ships. It contains the following modules:

- Low frequency (LF) mathematical model for the ship motions in the horizontal plane, see Ref. 4.
- Environmental force/moment generation model, to compute the environmental forces/moment acting on the ship.
- Control module, which applies the feedback position control on basis of position error and drift velocity, to determine the total required propulsive vector and the required thruster action.
- Thruster action model, which takes into account the thruster performance in the local flow conditions, including the effect of thruster-hull and thruster-thruster interaction, see Ref. 5.

To clarify the use of the program, it is useful to consider first the DP control loop and the particulars of a prototype control system.

DP Automatic Feedback Closed Loop Control System. The control loop for prototype and model test may be a system as is given in Fig. 5. The automatic closed loop control system as used during model tests is the so-called RUNSIM program. Referring to Fig. 5 and starting with the loop at the ship, the following sequence is applied:

- The position measurement of the ship, using the displacement and velocities (incl. noise) in surge, sway and yaw direction. The position prediction and estimate, using the Extended Kalman Filter in the automatic closed loop control system, is an almost purely LF signal for surge, sway and yaw. After the determination of the required position and heading of the vessel, the LF position error and drift is obtained in a ship fixed system of axis.
- The controller, which computes from the error and drift the required longitudinal and transverse force and the yaw moment (total required propulsive vector). In case of a PID controller the control coefficients are a restoring coefficient (P), a damping coefficient (D) and an integrator term (I). The first two terms determine the feedback performance, while the latter only acts to correct somewhat for a mean position error.
- The allocation, which is a computing module to allocate thrust and direction to the available thrusters is based on the total required propulsive vector. The thruster action is intended to move the ship back to the required position. However, the instantaneous environmental forces/moment may be higher than the thruster action, so that the position error at that time step will not improve (e.g. passing of the large waves in a group). This is a fundamental shortcoming of feedback control.

It must be noted that 3-axis DP has always a Reference Point (RP) and a Control Point (CP). The RP is the required position/heading of the ship with regard to earth. The CP is the point on and heading of the ship, which want to have coinciding with the RP in ideal cases. The difference between the position of RP and CP is called the error. The RP of the heading is to be set by the DP operator dependent on the weather directions (optimal heading), while in this study the CP is the centre of the drillfloor.

DP Simulations in the Low Frequency Time Domain. In the computations with the program DPSIM, a number of simplifications were applied, if compared to the prototype (or model test) situation:

- The LF mathematical model provides the actual position error and drift (no noise). So, application of a (Kalman) filter has no use. A phase delay, however, was applied.
- The integration coefficient in the PID controller was set to zero, because the way in which in prototype situations the mean position is corrected is usually a DP operator's decision very much dependent on the situation and personal preferences. Furthermore, it does not affect the conclusions as to the ship's DP performance.

Review of Computations. The DP computer simulation studies were applied to the Gulf of Mexico 10-year winter storm and the loop current storm as are indicated in Table 3. The DP stationkeeping ability was studied for a number of heading references for each of the design storms. A review of the storm conditions, the heading references and the results of the computations are given in Table 5. The system of coordinates for both the weather directions, the heading reference and the vessel motions is given in Fig. 6. All computations last for 3 hours full scale excl. start up time. In order to achieve Class 3 DP notation, it is necessary to demonstrate that the vessel can maintain station even in the event that any thruster has failed. The bow thruster (No. 4) is the most important thruster and was therefore considered inoperable for the majority of the tests. (Note: the vessel has 3 engine rooms, each of which are capable of delivering 50% of the required power so that loss of engine room does not result in loss of propulsion).

Before starting the computations the (optimal) control setting and the DP allocation strategy have to be determined.

Control Setting. The control setting (PD-coefficients) had to generate stable positioning and make effective use of the limited possibilities of the thrusters. The following aspects play a role:

- Since the thrusters could not reverse RPM, too frequent changes in rate of turn of the azimuthing thruster had to be avoided. The time to turn 180 degrees is 15 seconds, which may lead to destabilization if the thrust requirement is building up.
- The heading control would be very important, especially in these conditions in which the DP is taxed to the limits.

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Before starting the computations the (optimal) control setting and the DP allocation strategy have to be determined.
The control setting has been optimized for both the 10-year winter storm and the loop current storm. An example of the optimization is given in Table 4. For the 10-year winter storm the PD-coefficients as obtained from run No. 7 were chosen. Run No. 8 and 9 gave smaller standard deviations, but it was found that the system became too stiff resulting in a frequent change of the setpoints, which has to be avoided. For the loop current storm the PD-coefficients of run No. 14 were chosen. Control settings were adjusted in consultation with the vessel's DP system supplier.

DP Allocation Strategy. For the thruster layout a thrust allocation has been designed which would result in an effective control for heading as well as for surge and sway. The following considerations played a role in the design:

- Combined heading and surge control puts a high thrust requirement on the forward thrusters. Heading control is very important because loss of heading will immediately lead to a sharp increase of the transverse environmental load and sideways drift-off.
- The azimuthing of the thrusters allows to orient the thrust vector \( T \) in such a way that a significant transverse force can be generated without losing much force in longitudinal direction: e.g. at a thruster azimuth of 45 deg, 0.7 of \( T \) acts transverse and 0.7 of \( T \) acts longitudinal.
- The relatively small distance between the three azimuthing thrusters at the bow as well as between those at the stern, implies situations of thruster-thruster interactions, leading to thrust degradation. This has been avoided in the control system by the introduction of forbidden sectors for the thruster angles.
- Wind feed forward has been applied, because the wind load on the vessel is a significant part of the total environmental force. The estimated wind force acting on the vessel, established from the actual heading, the measured wind speed and the wind coefficients, was partially added to the feedback forces in the controller and thus provided the required longitudinal force, transverse force and moment.

Thus, the following allocation logic were designed for the DP control program for both DPSIM and RUNSIM:

- The thrusters would all be used for heading as well as surge and sway control.
- The thrusters would be steered in such a way that the incidence of thruster jet flow on the other thruster is avoided (forbidden sectors among the three thrusters at the bow and among those at the stern.). This is done by rotating the thruster jet flow away from the affected thruster. The resulting change in longitudinal and transverse force is compensated by also re-orienting the affected thruster. The forbidden sectors are 20 deg, a value based on the jet flow cone angle (about 4 deg) and the separation distance between the thrusters.
- Fixation of a thruster on a given orientation is not applied.
- If the forbidden sectors allowed, the two thrusters in the base of the forward triangle acted in tandem and the three thrusters aft acted in trio, thereby economizing their utilization.

**Thruster Allocation Algorithm.** Below the description of the allocation algorithm is given with intact thruster arrangement. For the damaged cases (failure of the forward most bow thruster), the algorithm was not modified. This represents a situation in which the DP control system does not 'know' that one thruster failed, which is the worst case scenario.

The allocation routine as used for DPSIM computations and RUNSIM measurements, taken into the correction for the forbidden sectors is as follows. The drillship is equipped with a total number of six thrusters (three aft thrusters, \( T_1 \) (stem), \( T_2 \), \( T_3 \) and three thrusters at the bow \( T_4 \) (bow) – \( T_5 \), \( T_6 \). This results in the following equations:

\[
F_{x_1} + F_{x_2} + F_{x_3} + F_{x_4} + F_{x_5} + F_{x_6} = X_{\text{REG}}
\]

\[
F_{y_1} + F_{y_2} + F_{y_3} + F_{y_4} + F_{y_5} + F_{y_6} = Y_{\text{REG}}
\]

\[
F_{y_1} a_1 + F_{y_2} a_2 + F_{y_3} a_3 = N_{\text{REG}}
\]


where \( F_{x_i} \) (\( i = 1, \ldots, 6 \)) and \( F_{y_i} \) are the thrust force components in \( x \) and \( y \) direction respectively, \( l_i \) is the longitudinal distance of the thruster \( T_i \) to the centre of gravity.

To minimize the degrees of freedom of the thrusters, the assumption was made that the thrusters react as if they are working in three groups. This assumption can be done if the thrusters in one group are positioned relatively close to each other. Furthermore, it is assumed that the centre of all groups are located on the longitudinal line through the centre of gravity. Further it is assumed that each of the thrusters in one group deliver the same force and under the same angle. The three aft thrusters (1, 2 and 3) were taken as group 1, the two middle thrusters (5 and 6) as group 2 and the front thruster (4) as group 3. This results in the following equations:

\[
X_1 + X_2 + X_3 = X_{\text{REG}}
\]

\[
Y_1 + Y_2 + Y_3 = Y_{\text{REG}}
\]

\[
Y_1 a_1 + Y_2 a_2 + Y_3 a_3 = N_{\text{REG}}
\]

where \( X_i = F_{x_1} + F_{x_2} + F_{x_3}, \) the group 1 force in \( x \)-direction, \( a_i \) is the average distance of the thrusters in a group relative to the centre of gravity.

First it is assumed that all thrusters contribute equally to deliver the required force in \( x \)-direction \( (X_{\text{REG}}) \). Therefore:

\[
X_3 = \frac{1}{6} X_{\text{REG}}, X_2 = \frac{1}{3} X_{\text{REG}} \text{ and } X_1 = \frac{1}{2} X_{\text{REG}}
\]

Now, we express the forces \( Y_2 \) and \( Y_1 \) in terms of \( Y_3 \):
\[ Y_1 = Y_{\text{REQ}} - Y_2 - Y_3 \]

\[ Y_2 = \frac{M_{\text{REQ}} - a_1 Y_1 - a_3 Y_3}{a_2} \]

Combining these two equations results:

\[ Y_1 = Y_{\text{REQ}} - \frac{M_{\text{REQ}} - a_1 Y_1 - a_3 Y_3}{a_2} - Y_3 \]

and after writing this out:

\[ Y_1 = A + BY_3 \]

\[ Y_2 = C - DY_3 \]

where:

\[ A = \frac{M_{\text{REQ}} - Y_{\text{REQ}} a_2}{a_2 - a_1} \]

\[ B = \frac{a_3 - a_2}{a_2 - a_1} \]

\[ C = \frac{M_{\text{REQ}} - Y_{\text{REQ}} a_1}{a_2 - a_1} \]

\[ D = \frac{a_3 - a_1}{a_2 - a_1} \]

The force \( Y_3 \) can now be written as:

\[ Y_3 = \frac{2AB + 3CD}{6 + 2B^2 + D^2} \]

However, a thruster can not deliver any force. It is restricted to a force \( F_{\text{max}} \) (saturation limit), so:

\[ F_3 = \sqrt{X_3^2 + Y_3^2} \leq F_{\text{max}} \]

therefore, if this \( F_3 \geq F_{\text{max}} \) the \( x \) and \( y \) components are reduced by the same factor \( F_{\text{max}}/F_3 \). The same applies for \( F_1 \) and \( F_2 \).

The above treated allocation routine is based on the thruster group model. An alternative allocation routine may be the optimum power model. In this model the thrusters can be steered individually (thruster force and azimuth angle) based on an optimum power algorithm while the directional priorities are still taken into account.

Model Tests

RUNSIM program. As in prototype and during model tests the dynamic positioning system may be an input-output system with an automatic feedback closed loop controller. An automatic DP system in its general terms contains hardware components and software control algorithms. The hardware components are:

- position reference system
- computer
- interface equipment
- power system
- thrusters.

The operation and use of the above equipment is controlled by the software, having the following components:

Input:
- position reference system measurements
- thruster control parameters
- feed forward signals

Control loop:
- mathematical model of ship response to external forces
- Kalman filter algorithm (position prediction model)
- feedback controller (PID)
- thrust allocation algorithm
- status monitoring/warning systems

Output:
- thruster control commands
- graphic control commands
- graphic display
- data log

The systematic illustration of the automatic closed loop control system is given in Fig. 5. For the model tests the mentioned hardware and software system is integrated in the so-called RUNSIM program. For more details in the hardware and software of the control system, see Refs. 6, 7, 8, 9 and 10. A review of the storm conditions applied and the model tests performed are given in Table 3 and 5 respectively.

Optimization of the Coefficients. Prior to the tests, the control settings were checked with the results of the computations in the same weather conditions. After the optimization the same values were found as given in Table 4. For the Kalman setting in the EKF the following gains were taken (Fig. 5):

\[ K_{L1} = 5.10^{-4}, \quad K_{L2} = 5.10^{-3} \quad \text{and} \quad K_{L3} = 5.10^{-4} \]

Model Test Results. All measurements last for a duration of 3 hours full scale excl. 0.5 hour start up time. The results of the test in terms of statistical values are given in Table 5. For the system of coordinates, see Fig. 6. For all model tests thruster No. 4 was set non-active (redundancy).

Also sudden wind squall condition were investigated. The investigation was carried out by means of model tests only. The weather condition of the sudden wind squall condition is shown in Table 3. In the initial condition the collinearly directed waves and current are present (\( H = 3.5 \text{ m} \) and \( V = 6 \text{ m/s} \)) with \( \Psi_{R} = 0^\circ \). It is assumed that due to a thunderstorm a beam wind is occurring increasing from 0 to 26 m/s in 10 minutes. By changing the heading set point \( \Psi_{R} \) continuously from \( 0^\circ \) to \( 90^\circ \) the DP capability was investigated.

The results are presented in Fig. 7. The result of the test was that the vessel can keep station under the condition that all 6 thrusters were active (saturation 760 kN).
Discussion of Results
In the following the results of the DPSIM computations and the model tests will be discussed. The results are given in Tables 4 and 5.

In order to find the optimal DP-coefficients a relatively large number of computations are necessary prior to the final runs. Actually this optimization have to be carried out for each different weather condition. Future work has to be carried out by applying an adaptive control system for the DP-coefficients in case the weather conditions are changing. The merit of the optimal coefficients is not only the standard deviations of the motion but also the rate of turn of the azimuth angles. Further it is found that the choice of the PD-coefficients may be sensitive to the optimal performance of the DP system (Table 4).

In case the chosen reference heading is unfavourable with regard to the weather directions the vessel may not be able to keep station. In this case a loss of heading occurs followed by a sharp increase of the transverse environmental loads and a sideways drift-off. From the results in the 10-year storm and loop current condition it can be concluded that the predictions of drift-off as given by DPSIM agrees very well with the results of the model tests. This means that the thruster-(inter)action and the environmental loads in the computer program are rather well modelled with regard to prototype (model tests).

In the 10-year storm condition with the wind directions under 202.5° and 225° the results of the computations in terms of standard deviation of the motions and the thruster forces corresponds rather well with the results of the model tests. For the wind direction of 270° the results of the computations and model tests differ to some extend.

In the loop current condition with the waves and wind directions perpendicular to the current direction the results of the computations in terms of standard deviations of the motions and the thruster forces agrees rather well with the results of the model tests. In case the waves and current are directed co-linearly the computations show a decrease of the thruster forces. This may be caused by the fact that in the computations the increase of the wave drift forces due to the strong current was not taken into account.

Conclusions
From the results of the study the following conclusions can be drawn:

1) By means of the thruster-interaction insight can be obtained in the performance of the thrusters. Probably due to the tilting of the nozzles by 5° the thruster-hull interaction is relatively small and the effect of the bilge keels on the thruster-hull interaction is negligibly small.

In order to prevent thrust losses due to the thruster-thruster interaction it is recommended to apply forbidden sectors in the thruster allocation algorithm. The thruster-thruster interaction tests can provide data for the angle of the forbidden sectors.

2) In order to find the optimal DP-coefficients a relative large number of computations is necessary. The merit of the optimal coefficients is not only the standard deviation of the motion but also the rate of turn of the azimuth angles.

3) From the results in the 10-year storm and the loop current condition it can be seen that the predictions of drift-off as given by DPSIM agree very well with the results of the model tests. This means that the thrusters-(inter)action and the environmental loads as simulated in the computer program agree rather well with prototype.

4) In case the vessel can keep station the majority of the results of computations corresponds rather well with the results of the model tests.

5) It is necessary to run calibrated time domain simulation programs and/or model tests to assess DP stationkeeping capability of a 3-axis weathervaning vessel. Selection of optimum heading and DP constants is essential. Static analysis is inadequate for monohulls. When drift-off occurred, it was typically after many minutes exposure to the storm.

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References
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TABLE 1 - MAIN PARTICULARS AND STABILITY DATA

<table>
<thead>
<tr>
<th>Designation</th>
<th>Symbol</th>
<th>Unit</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars</td>
<td>Lₚ₀</td>
<td>m</td>
<td>213.00</td>
</tr>
<tr>
<td>Breadth</td>
<td>B</td>
<td>m</td>
<td>42.00</td>
</tr>
<tr>
<td>Depth</td>
<td>D</td>
<td>m</td>
<td>20.00</td>
</tr>
<tr>
<td>Scantling draft (even keel)</td>
<td>T</td>
<td>m</td>
<td>13.00</td>
</tr>
<tr>
<td>Displacement weight (open moonpool)</td>
<td>Δ</td>
<td>tf</td>
<td>103,770</td>
</tr>
<tr>
<td>C.o.G. above keel</td>
<td>GK</td>
<td>m</td>
<td>12.06</td>
</tr>
<tr>
<td>C.o.G. forward of station 0</td>
<td>LCG</td>
<td>m</td>
<td>102.88</td>
</tr>
<tr>
<td>Metacentric height</td>
<td>GM</td>
<td>m</td>
<td>6.30</td>
</tr>
<tr>
<td>Longitudinal radius of gyration in air</td>
<td>kᵧᵧ</td>
<td>m</td>
<td>48.00</td>
</tr>
<tr>
<td>Transverse radius of gyration in air</td>
<td>kₓₓ</td>
<td>m</td>
<td>13.40</td>
</tr>
<tr>
<td>Vertical radius of gyration in air</td>
<td>kᵧz</td>
<td>m</td>
<td>48.60</td>
</tr>
<tr>
<td>Roll period</td>
<td>Tᵣ</td>
<td>s</td>
<td>11.50</td>
</tr>
<tr>
<td>Bilge keel length (station 3-15)</td>
<td>l</td>
<td>m</td>
<td>127.8</td>
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<tr>
<td>Bilge keel height</td>
<td>h</td>
<td>m</td>
<td>.514</td>
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</table>

TABLE 2 - PARTICULARS OF PROPELLER REPRESENTED BY THE STOCK PROPELLER MODELS

<table>
<thead>
<tr>
<th>Designation</th>
<th>Symbol</th>
<th>Unit</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller diameter</td>
<td>D</td>
<td>mm</td>
<td>3800</td>
</tr>
<tr>
<td>Pitch adjusted at 0.7R</td>
<td>P₀.7</td>
<td>mm</td>
<td>3610</td>
</tr>
<tr>
<td>Pitch ratio at 0.7R</td>
<td>P₀.7/D</td>
<td>-</td>
<td>.950</td>
</tr>
<tr>
<td>Boss-diameter ratio</td>
<td>d/D</td>
<td>-</td>
<td>.288</td>
</tr>
<tr>
<td>Expanded blade area ratio</td>
<td>Aₑ/A₀</td>
<td>-</td>
<td>.487</td>
</tr>
<tr>
<td>Number of blades</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Power per unit</td>
<td>P</td>
<td>MW</td>
<td>4</td>
</tr>
<tr>
<td>Nozzle length</td>
<td>L</td>
<td>mm</td>
<td>1930</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>D</td>
<td>mm</td>
<td>3854</td>
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TABLE 3 - DESIGN WEATHER CONDITION

<table>
<thead>
<tr>
<th>Hₛ</th>
<th>Tₛ</th>
<th>Dir.</th>
<th>Vₛ</th>
<th>Dir.</th>
<th>Vₑ</th>
<th>Dir.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[m]</td>
<td>[s]</td>
<td>[deg]</td>
<td>[m/s]</td>
<td>[deg]</td>
<td>[m/s]</td>
<td>[deg]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gulf of Mexico (Jonswap γ = 3.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-year winter storm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td>10.6</td>
<td>180</td>
<td>26</td>
<td>202.5</td>
<td>.6</td>
<td>180</td>
</tr>
<tr>
<td>5.8</td>
<td>10.6</td>
<td>180</td>
<td>26</td>
<td>225</td>
<td>.6</td>
<td>180</td>
</tr>
<tr>
<td>5.8</td>
<td>10.6</td>
<td>180</td>
<td>18</td>
<td>270</td>
<td>.6</td>
<td>180</td>
</tr>
<tr>
<td>Loop current condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td>10.6</td>
<td>180</td>
<td>18</td>
<td>202.5</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>5.8</td>
<td>10.6</td>
<td>225</td>
<td>18</td>
<td>202.5</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>5.8</td>
<td>10.6</td>
<td>270</td>
<td>18</td>
<td>270</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>Sudden wind squall condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>9.0</td>
<td>180</td>
<td>0-26</td>
<td>270</td>
<td>.6</td>
<td>180</td>
</tr>
<tr>
<td>North West Atlantic - summer months (Jonswap γ = 3.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.8</td>
<td>14.2</td>
<td>180</td>
<td>30</td>
<td>202.5</td>
<td>1.3</td>
<td>180</td>
</tr>
<tr>
<td>8.8</td>
<td>14.2</td>
<td>225</td>
<td>30</td>
<td>202.5</td>
<td>1.3</td>
<td>180</td>
</tr>
<tr>
<td>8.8</td>
<td>14.2</td>
<td>270</td>
<td>30</td>
<td>270</td>
<td>1.3</td>
<td>180</td>
</tr>
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</table>
### TABLE 4 - OPTIMIZED SETTING CONTROL COEFFICIENTS (THRUSTER #4 NON-ACTIVE)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Px [kN/m]</th>
<th>Dx [kN/m/s]</th>
<th>Dy [kN/m/s]</th>
<th>Pw [kN]</th>
<th>Dw [kN/m rad/s]</th>
<th>x [m]</th>
<th>y [m]</th>
<th>θ [deg]</th>
<th>σ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>3700</td>
<td>50</td>
<td>7731</td>
<td>1E6</td>
<td>4.4E7</td>
<td>-58.8</td>
<td>4.3</td>
<td>234</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>5110</td>
<td>70</td>
<td>8334</td>
<td>1E6</td>
<td>4.4E7</td>
<td>-34.8</td>
<td>3.2</td>
<td>20.5</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>1500</td>
<td>150</td>
<td>3000</td>
<td>1E6</td>
<td>1.5E6</td>
<td>drift-off</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>1500</td>
<td>250</td>
<td>3000</td>
<td>1E6</td>
<td>1.5E6</td>
<td>drift-off</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>2000</td>
<td>150</td>
<td>3000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>drift-off</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>2000</td>
<td>250</td>
<td>3000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>drift-off</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>150</td>
<td>4000</td>
<td>150</td>
<td>3000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>-14.8</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>150</td>
<td>4000</td>
<td>150</td>
<td>7000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>-14.8</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>150</td>
<td>4000</td>
<td>150</td>
<td>7000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>-15.0</td>
<td>9.5</td>
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</tr>
</tbody>
</table>

Loop current condition: wave dir. = 270°; wind dir. = 270°; current dir. = 180°; ΨRP = 30°

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Px [kN/m]</th>
<th>Dx [kN/m/s]</th>
<th>Dy [kN/m/s]</th>
<th>Pw [kN]</th>
<th>Dw [kN/m rad/s]</th>
<th>x [m]</th>
<th>y [m]</th>
<th>θ [deg]</th>
<th>σ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30</td>
<td>3700</td>
<td>50</td>
<td>7731</td>
<td>1E6</td>
<td>4.4E7</td>
<td>drift-off</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>60</td>
<td>5110</td>
<td>70</td>
<td>8334</td>
<td>1E6</td>
<td>4.4E7</td>
<td>drift-off</td>
<td>2.8</td>
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</tr>
<tr>
<td>12</td>
<td>150</td>
<td>1500</td>
<td>150</td>
<td>3000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>drift-off</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>150</td>
<td>1500</td>
<td>250</td>
<td>3000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>drift-off</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>150</td>
<td>4000</td>
<td>150</td>
<td>3000</td>
<td>1E6</td>
<td>6.0E6</td>
<td>-5.1</td>
<td>4.1</td>
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</tr>
</tbody>
</table>

### TABLE 5 - RESULTS OF COMPUTATIONS AND MODEL TESTS (Thruster #4 non-active)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>ΨRP [deg]</th>
<th>m</th>
<th>x</th>
<th>m</th>
<th>y</th>
<th>m</th>
<th>θ</th>
<th>m</th>
<th>T1 [kN]</th>
<th>σ</th>
<th>T5 [kN]</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-year winter storm Gulf of Mexico: wave dir. = 180°; wind dir. = 202.5°; current dir. = 180°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test 0 Drift-off
Calc. 0 Drift-off
Test 10 -0.1 2.0 -4.0 2.6 12.2 1.5 377 82 437 107
Calc. 10 -6.9 2.8 1.2 3.6 8.9 1.8 390 133 389 167
Test 20 -2.1 2.3 5.0 1.4 20.2 1.3 356 90 398 124
Calc. 20 -8.6 2.5 7.5 4.3 21.1 1.9 316 105 355 109

wave dir. = 180°; wind dir. = 225°; current dir. = 180°

Test 30 -3.5 3.6 8.8 7.8 32.1 1.7 360 109 422 145
Calc. 30 -14.9 3.6 8.8 7.8 30.3 3.9 361 118 440 161

wave dir. = 180°; wind dir. = 270°; current dir. = 180°

Test* 15 -6.9 6.2 -7.1 3.2 17.7 3.1 338 189 480 228
Calc.* 15 -3.3 3.9 -14.3 8.6 18.1 7.3 208 115 543 250
Test* 30 -5.5 7.0 -4.1 3.6 32.7 2.8 297 185 440 223
Calc.* 30 -2.7 3.7 -10.0 15.4 24.4 6.4 177 85 505 260
Test* 40 -5.4 6.0 -1.4 3.7 43.2 2.6 270 164 410 206
Calc.* 40 -5.9 5.1 -4.6 9.8 36.2 4.4 188 64 442 246

wave dir. = 225°; wind dir. = 202.5°; current dir. = 180°

Test 5 -6.8 4.2 -1.9 8.7 4.4 4.2 416 128 605 166
Calc. 5 -6.6 2.0 -6.8 5.1 5.2 1.0 299 88 343 158
Test 15 -6.0 2.2 4.6 2.9 15.5 2.4 387 100 558 165
Calc. 15 -11.0 1.5 4.8 3.7 16.4 1.9 230 71 324 64
Test 25 Drift-off
Calc. 25 Drift-off

wave dir. = 270°; wind dir. = 270°; current dir. = 180°

Test 20 Drift-off
Calc. 20 Drift-off
Test 30 -12.1 4.2 -6.1 8.2 33.7 3.9 389 160 582 174
Calc. 30 -5.1 4.1 -6.5 9.2 29.3 1.9 240 112 438 256
Calc 40 Drift-off
Calc 40 Drift-off

1) Pw = 1.5E6 kN/m rad
Fig. 1 - General arrangement of the drilling vessel

Fig. 2 - Thruster-hull interaction thruster No. 5
Fig. 3 - Thruster-thruster interaction thruster No. 4 and No. 5

Fig. 4 - Thruster-thruster interaction thruster No. 1 and No. 2
OTC 8854 HYDRODYNAMIC RESEARCH ON AND OPTIMIZING DYNAMIC POSITIONING SYSTEM OF A DEEP WATER DRILLING VESSEL

Fig. 5 - Automatic closed loop control system
Fig. 6 - System of coordinates

Fig. 7 - Sudden wind squall test (6 thrusters active)