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OPERATIONS SESSION

Planning of drilling operations in extreme ocean currents: experience from time-domain simulations and full-scale validation on Maersk Venturer

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Abstract

Most of the drilling operations in deep water are performed in Dynamic Positioning (DP) mode and the ability of the DP system to maintain position and heading within the required accuracy is one of the critical aspects to evaluate in the planning phase.
The aim of this paper is to share experiences in planning DP drilling operations in a harsh environment dominated by extreme ocean currents. The paper will present the full-scale trials performed with the drill ship Maersk Venturer, an enhanced Samsung Drilling V-class series drill ship belonging to Maersk, outside South Africa where the environmental conditions were particularly harsh, including high current speeds and large waves. Maersk Venturer is installed with an advanced Thruster and Engine control, which is governed by a specially designed Power Managements System, including fast blackout recovery and enhanced blackout prevention devices. This differentiates it from the standard series of Samsung drill ships, making the total DP system very robust and enhanced.
The primary project goal was to understand the performance of the drill ship in such challenging environmental conditions. The secondary goal was to evaluate if the use of comprehensive dynamic operability analyses performed by time-domain simulations could provide important results for understanding the vessel performance and limitations, in turn providing valuable input to operational risk assessment and planning.
The paper will touch upon the challenges of choosing the most robust heading strategy when both high ocean currents and large waves occur at the same time, the robustness of the positioning strategy upon environmental direction changes, the resulting vessel footprints during and just after the worst case single failure (transient), and how to include the results from these analyses in the Well Specific Operating Guidelines. A comparison between the full-scale trials and simulations will also be provided.

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Introduction

The ongoing demand for energy, together with decreasing supplies of traditional fossil fuels, is pushing oil and gas exploration further offshore and deeper underwater. As drilling is moving toward more extreme environments, the operators and oil companies are facing new challenges, both technologically and operationally. With the consequent increase in cost and risk of deepwater exploration, operational risk management tools have become key elements for supporting incident free and efficient operations.
The majority of deep-water drilling operations are performed by dynamic positioning (DP) vessels thus relying heavily on the vessel's capability to maintain its position and heading, typically also after a single failure. However,

the vessel station-keeping capability is only one of the requirements for carrying out an operation in a safe and efficient manner. In drilling operations there are other criteria to consider, for example rig motion performances (heave, pitch, and roll) and equipment used to mitigate their impact, which are as important as station keeping for the smooth conduct of such complex projects. For these operations, where the stakes are high both regarding cost and safety, it is essential that the vessel operators have a full understanding of the vessel capability on different environmental conditions and can rely on tools that can provide realistic estimates of the vessel DP Capability, optimum position and predict the vessel motions with sufficient accuracy. These are vital aspects to confirm first of all the project feasibility, then in a second phase to plan activities, determine the operational weather window and ultimately to maximize the vessel operability to keep associated risks and costs under control, keeping in mind that decisions made on wrong assumptions may always compromise the safety of the operation.

The aim of this paper is to share experiences in planning DP drilling operations in a harsh environment dominated by extreme ocean currents. The paper will present full-scale trials performed with the drill ship Maersk Venturer off South Africa where the environmental conditions are well known to be particularly harsh, combining high current speeds, large waves and strong winds.
The sea trials were carried-out as part of the drillship mobilization for the Raya exploration project (offshore Uruguay) on the way between Singapore and Montevideo with specific objectives for the operator, Total E&P.
The primary project goal was to confirm the robust station keeping and rig motion performances of the drill ship that were pre-assessed in similar challenging environmental conditions in the context of the Raya project preparation. The secondary goal was to evaluate if the use of comprehensive dynamic operability analyses performed by time-domain simulations could provide important results for understanding the vessel performance and limitations, in turn providing valuable and reliable input to operational risk assessment and planning.
The third objective was to complete the extensive preparation achieved through different workshops and simulator training sessions together with the project engineers, service companies and the crew. The fourth and final objective was to freeze the marine operating limits defined previously as part of the preparation in order to tackle serenely the well activity.

The paper will touch upon the challenges of selecting the optimal vessel heading when both high ocean currents and large waves occur at the same time, the robustness of the positioning strategy upon environmental direction changes, the resulting vessel footprints during and just after thruster failure (transient).
The second part of the paper presents a comparison between the full-scale trials and simulations performed with DynCap, a software tool base on vessel specific simulator, developed by DNV GL Marine Cybernetics Services.

Challenges in DP operational planning in harsh weather

There are many challenges when operating in deepwater and in harsh environment. In general, the choice of heading for DP operations would always be the best compromise between power usage (including power availability post failure) and vessel motions. In most current conditions, head to wind and waves is generally the best option (for a monohull design especially). However, feedback from rig owners in the Gulf of Mexico, where strong loop currents (2 to 4 knots) are common, indicates that a minimum power heading is selected provided that it does not introduce unacceptable motions or cause rubbing of the downlines/drillpipe/riser etc. This means that the preferred approach is to find a good balance between a smooth ride, drill-pipe rubbing and minimal loads on the thrusters. In other words, the best compromise for keeping rig motion and station keeping within the operating limits. This is not always easy to achieve especially when wind, wind-sea, swell and current are uncorrelated. Another thing to consider is whether the drill floor has any restrictions relating to relative wind direction, as there may be requirements to keep any gas escapes from blowing towards either machinery or accommodation intakes.
Challenges may arise when both strong current and large waves are present. Which heading would provide the best compromise between power usage and contained motions? In case current and waves come from opposite directions, should the vessel face the current or face the waves? What is the positioning robustness upon heading changes or sudden environmental direction shifts? Can different DP control system settings such as control gains and yaw rate of turn settings affect the positioning performance during heading change? This paper will try, by sharing experience from the trials performed on the Maersk Venturer, to answer some of the questions above.

Experiences and results from the sea trials

This section describes the full-scale DP trial performed with the drillship Maersk Venturer in February 2016, during its passage from Singapore to Uruguay. The trials were conducted in three locations along the South African coast,

with the main goal of evaluating the vessel's station-keeping performance while exposed to the Agulhas current and the rig motion when exposed to medium/high waves.

Vessel description

Maersk Venturer (IMO: 9633563) is a drilling ship built in 2014 (Samsung 96K design) for ultra-deep-water drilling and development. Featuring dual derrick and large subsea work and storage areas, the design allows for efficient well construction and field development activities through parallel and offline activities. Maersk Venturer has 228 m length overall and beam of 42 m. Her gross tonnage is 60683 tons. The vessel is equipped with six 5500 kW ducted azimuth thrusters. The thruster layout is presented in Figure 2. The main particulars and the load condition utilized during the trials are listed in Table 1 and Table 2 respectively. More information about the drillship can be found in [9].

Figure 1: Maersk Venturer, courtesy of Maersk

Table 1: Main particulars

Description	Symbol	Unit	Value
Length over all	L_{OA}	m	228.00
Length between perpendiculars	L_{PP}	m	219.00
Breadth	B	m	42.00

Table 2: Loading Condition

Description	Symbol	Unit	Value
Draught	T	m	11.00
Mass displacement	m	tonnes	88218
Transverse metacenter height	GMT	m	3.90

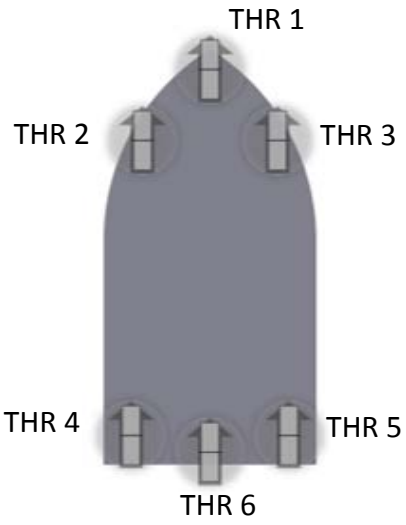


Figure 2: Thruster layout

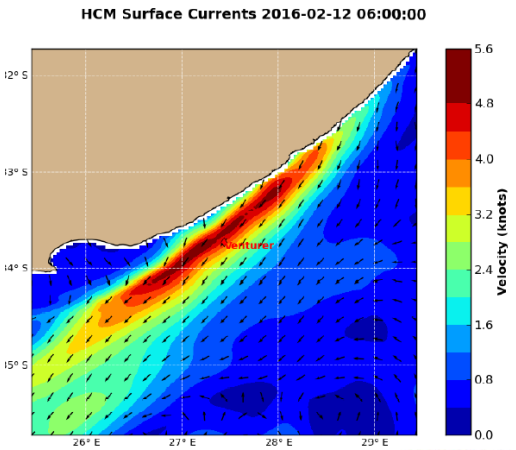
Sea trial description

The trials were performed throughout the 12th to the 15th of February 2016. The trials were performed in the locations listed in Table 3.

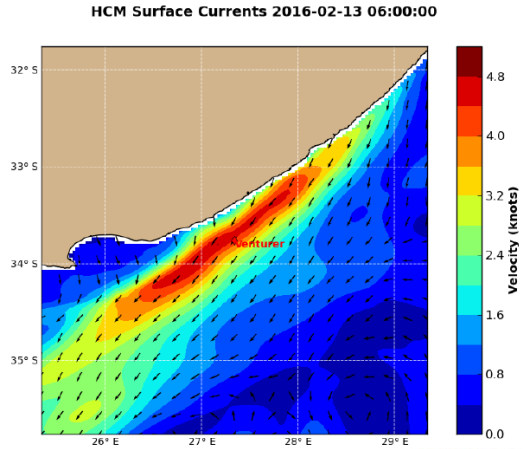
Table 3: Location of the sea trials

Date	Location	Coordinates
2016-02-12	South of East London	33°43'S, 27°26'E
2016-02-13	South of East London	33°45'S, 27°20'E
2016-02-14	Southeast of Brulpadda well location	36°05'S, 23°05'E
2016-02-15	Southwest of Brulpadda well location	36°21'S, 22°00'E

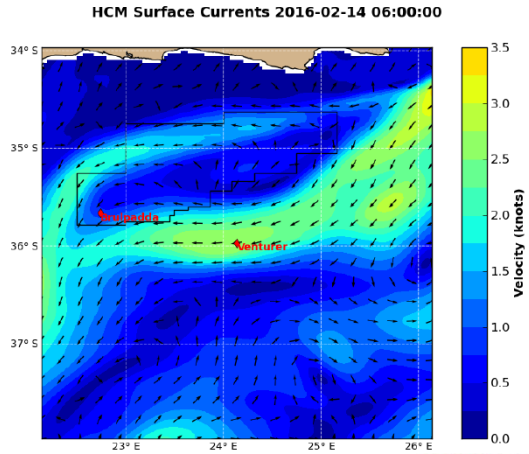
As the main goal of the trials was exposure to the Agulhas current, the choice of each location rested primarily on current forecasts. In Figure 3, obtained from [10], the trial locations have been overlaid on the most recent current forecast for that day. In each figure, a red diamond marks the actual location of the vessel.



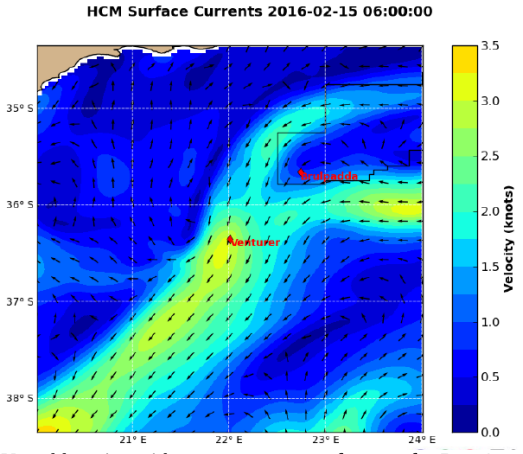
Vessel location with respect to current forecast for Day 1



Vessel location with respect to current forecast for Day 2



Vessel location with respect to current forecast for Day 3



Vessel location with respect to current forecast for Day 4

Figure 3: Vessel locations and current forecast for the trial days

Available measurements

All data available to the DP system has been logged with a connected DP History Station, including but not limited to:

- Wind sensor data (speed at 10 m over sea surface, direction)
- GPS data (longitude, latitude)
- Gyro data (heading, rate of turn)

- VRU data (heave, roll, pitch)
- Thruster data (azimuth, RPM, load)
- Generator data (load)

The wave measurement was performed with an onboard wave radar. Wave direction was not among the available data, and has been observed visually by the attendees of the trials. The available data is part of the Standard Wave Analysis Package [11] including, among others:

Table 4: Wave radar data

Variable	Description	Unit
H_s	Significant wave height	cm
H_{max}	Height of highest wave	cm
T_p	Average wave peak period	s
F_p	Peak frequency of wave spectrum	mHz

Ocean current was measured with an Acoustic Doppler Current Profiler (ADCP). The measured data includes:

- Current speed at depth intervals of 32 m
- Current direction depth intervals of 32 m

In order to avoid interference with the hull and the thrusters, the instrument was lowered to a depth of 17 m so that the shallowest available reading was given at a depth of 49 m. Following a discussion between the participants of the trials and referring to the existing Metocean data, hindcasts, older current measurements and current profiles drawn-up by Total Metocean Specialists from the same area [15], the surface current speed was assumed to be 5% higher than the measurement at 49 m. The direction measurements were given as magnetic direction, then corrected with the expected magnetic deviation as well as measurements from the onboard water velocity log, giving the estimated true current direction. The current direction and magnitude values were also used to confirm the accuracy of the current forecasts. The ADCP was deployed each day before the trial sessions began. The speed and direction measurements, once corrected, were assumed to be constant for the trial sessions the same day. The current speed was however monitored during the day by looking at the onboard water velocity log to check for possible significant changes.

Angle convention

In this paper the all environmental directions are relative to north (coming from direction) increasing clockwise, meaning that zero degrees is coming from north. The vessel heading is defined as 0 degrees pointing toward north and increasing clockwise. An example is given in Figure 4.

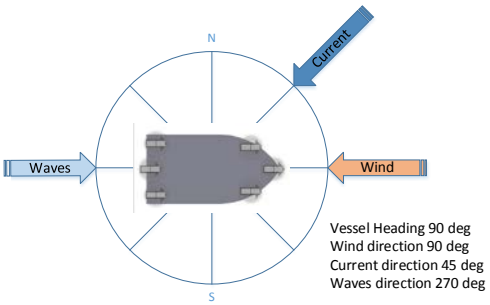


Figure 4: Mean environmental directions

Summary of the trial sessions

Table 5 includes all the trials performed during the 4 days. Every day started with the deployment of the Doppler current profiler. Most of the tests lasted for about 30 min. The largest values for wind speed, significant wave height and current speed are highlighted with orange in the table. Four types of tests were carried out:

- Station-keeping in DP at various heading
- Significant and sudden change of heading in DP
- Station-keeping in DP – worst single thruster failure and worst case single failure
- Track-following in DP
- Simulated power blackout tests in addition with drift off tests
- Joystick tests

Station-keeping trials were performed to evaluate the DP station-keeping performance with environmental conditions attacking from different angles. Significant and sudden changes of heading (180 degrees) in DP mode where carried out for checking the positioning sensitivity to heading change in severe weather conditions and for assessing the impact of DP settings and human intervention in this particular scenario. Station-keeping trials with thruster(s) failure where performed to assess the positioning sensitivity upon thruster failures (transient analysis). One track-following test was performed to evaluate the vessel capacity and stability of DP system when following a track in severe conditions, simulating in that way a drift running or a controlled drift situation. Power blackout tests, performed by disabling all the thrusters, done to measure the drift off speed, evaluate the time to disconnect and to check the conservatism (or not) of the DP system drift-off simulations. Test in Joystick mode were performed to collect valuable data for tuning the DynCap vessel simulator to see if the accuracy of the simulations would improve by adapting the models to full-scale data. Data were collected with 1 Hz sampling rate.

Table 5: Summary of trials sessions

#	Description	Vessel Heading [deg]	Thruster configuration	Wind (10 m/ 1 min mean)		Waves*			Current	
				Speed [m/s]	Dir. [deg]	H_s [m]	T_p [s]	Dir. [deg]	Speed [m/s]	Dir. [deg]
1.	DP station-keeping, ADCP deployment	250	Thruster 2 offline	10.35	76.2	1.54	10.6	70	1.95	45
2.	Heading change to face current	225 to 50	Intact	13.27	73.94	2.55	9.8	80	1.95	45
3.	DP station-keeping	50	Intact	13.26	68.0	2.62	8.30	70	1.95	45
4.	DP station-keeping	20	Intact	12.39	93.8	2.58	9.50	80	1.95	45
5.	DP station-keeping, intact to failure condition	55	Thruster 1 first on then off	9.39	62.8	2.85	9.00	75	1.95	45
6.	DP station-keeping, intact to failure condition	45	Thruster 1&4 first on then off	13.77	46.2	2.66	10.20	50	1.95	45
7.	DP station-keeping	47	Intact	9.65	63	2.92	9.5	80	1.95	45
8.	DP station-keeping, ADCP deployment	35	Thruster 2 offline	12.35	59.7	2.59	9.4	50	2.11	45
9.	DP station-keeping	35	Intact	12.95	53.0	2.68	11.0	50	2.11	45
10.	DP station-keeping	20	Intact	12.58	55.7	2.58	11.10	53	2.11	45
11.	DP station-keeping	15	Intact	12.47	56.6	2.52	11.30	53	2.11	45
12.	DP Heading change, stern towards current	15 to 210	Intact	8.36	51.0	2.40	11.5	50	2.11	45
13.	DP station-keeping	210	Intact	6.38	38.9	2.55	11.0	30	2.11	45
14.	DP Heading change to face current	210 to 35	Intact	9.46	39.4	2.80	10.3	40	2.11	45
15.	DP Auto track	40	Intact	6.09	16.9	2.65	9.8	180	2.11	90
16.	Blackout / drift off test	40	All thrusters offline	4.68	-3.53	2.73	11.3	30	2.11	45
17.	DP station-keeping, ADCP deployment	250	Thruster 2 offline	16.91	-84.4	4.19	8.9	270	1.13	90
18.	DP station-keeping	205	Intact	16.84	-48.0	4.80	9.10	250	1.13	90
19.	DP station-keeping	160	Intact	17.55	-55.2	4.35	9.10	250	1.13	90
20.	DP station-keeping	115	Intact	16.88	-87.3	3.69	9.80	270	1.13	90

21.	DP station-keeping	70	Intact	16.41	-80.9	3.24	9.90	270	1.13	90
22.	DP station-keeping	25	Intact	16.28	-74.7	4.25	10.00	270	1.13	90
23.	DP station-keeping	340	Intact	18.08	-93.6	3.99	10.00	270	1.13	90
24.	DP station-keeping	295	Intact	17.36	-87.4	4.59	10.00	270	1.13	90
25.	DP station-keeping	250	Intact	18.19	-76.3	5.42	10.0	270	1.13	90
26.	DP station-keeping, ADCP deployment	250	Thruster 2 offline	11.45	-77.9	3.58	10.1	270	1.63	20
27.	DP station-keeping	275	Intact	10.37	-81.3	3.52	9.7	270	1.63	20
28.	DP station-keeping	325	Intact	10.33	-89.9	3.14	9.6	270	1.63	20
29.	DP station-keeping	335	Intact	9.05	-97.7	3.01	8.8	270	1.63	20
30.	DP station-keeping	15	Intact	7.72	-135.1	3.05	10.6	270	1.63	20
31.	Joystick tests	-	Intact	6.42	-158.1	3.88	8.9	270	1.63	20

* H_{max} is estimated to be twice the value of Hs in accordance with general knowledge of wave ratios in the area [15]

Results and discussion

This section includes the most relevant results from the trials.

Station-keeping trials

During the four days of testing, 23 trials in DP station-keeping mode were conducted. The current speed was quite high in all tests, wind speed ranged from about 8 m/s to 18 m/s and the significant wave height from about 1.5 m to almost 5.5 m. The largest position deviation recorded has been 8 m (trial 23). In this trial, the heading setpoint was non-optimal regarding minimum environmental loads as the weather was attacking from the quarter toward the stern of the vessel, see Figure 5. This may have resulted in a large force due to slowly varying wave drift and current.

For all the other trials, the position and heading deviation has been limited to 6 m and about 6 degrees. The maximum position and heading deviations are presented in Figure 7 and Figure 8, respectively.

Besides trial 23, described earlier, it is worthy to notice that in the trials with the largest heading deviation (trial 1, 4 and 11), the heading deviation was not around zero when the test started, suggesting that DP control system did not reach a stable condition yet. Due to time limitation, it was not possible to wait for the DP control system to stabilize around zero heading deviation on each test.

Trials performed to compare the vessel performance with either the bow or the stern against the current direction, with current and waves acting on opposite directions (Trial 17, 24 and 25 against trial 21) showed that the vessel station-keeping capability was comparable with no evident gains for either strategies.

With environmental loads acting from the same direction (trial 9 against 13), the positioning performance suggests that there is no evident gain on positioning the bow or the stern against the environmental directions. The situation may be different with larger waves or higher current speed.

The robustness of the station-keeping positioning was tested by selecting the heading setpoint away from the optimal heading (the one which requires the minimum power). For Trial 11, for example, the heading was about 35 degrees off the mean environmental direction (30 degrees from the current direction). In this trial the vessel was about at its station-keeping limits with the position deviation that reached 5 m and the heading deviation 6 degrees. In this trial the maximum thruster power has reached almost 100 %. There were other trials where the vessel heading was set even further away from 30 degrees from the optimal heading, trials 18, 19, 22 and 23. From the positioning results, it can be seen that the position deviations (besides trial 23) was contained within 6 m and the heading deviation within 4 degrees.

The motion in heave, roll and pitch, as shown in Figure 9, Figure 10 and Figure 11, show that the vessel was very stable in all tested conditions, suggesting that for the environmental conditions encountered during the trials, there is not evident benefit on positioning the bow against the waves or against the current when they act in opposite directions. The same conclusion can be drawn when the environmental loads are attacking from the same direction. Figure 12 shows the mean and maximum total thruster power utilization for all the tests. The total thruster power utilization is computed by summing the individual utilization from each thruster at each time step and diving this by the total power for propulsion (5500 kW x 6).

In general, the crew was very satisfied with the vessel positioning performance in all conditions.

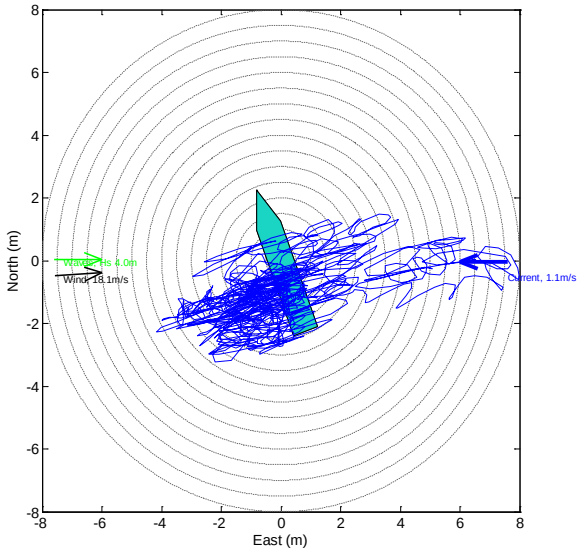


Figure 5: Measured vessel footprint from trial 23

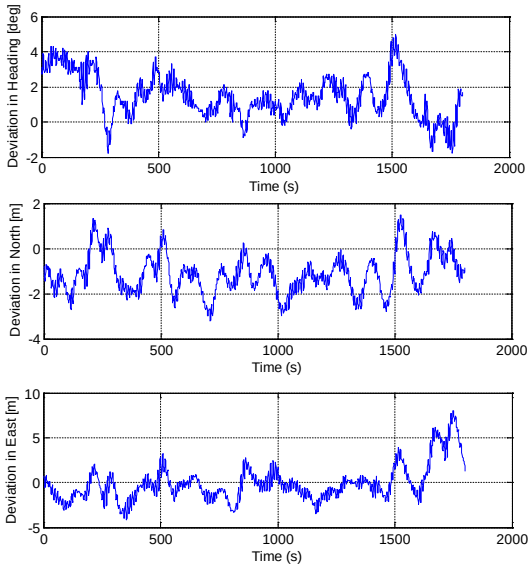


Figure 6: North, East and heading deveiaion from setpoint

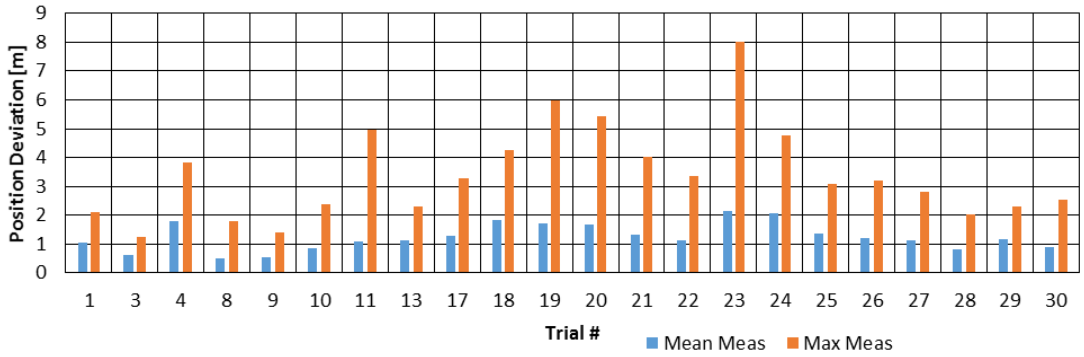


Figure 7: Position deviation for station-keeping trials

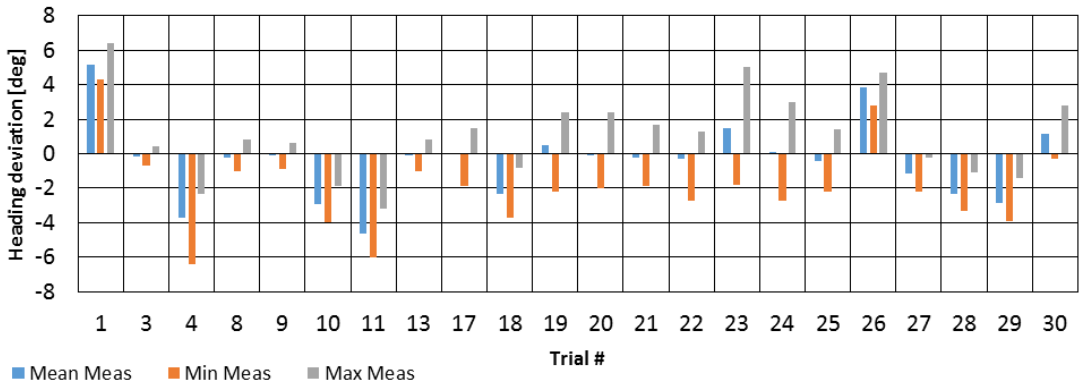


Figure 8: Heading deviation for station-keeping trials

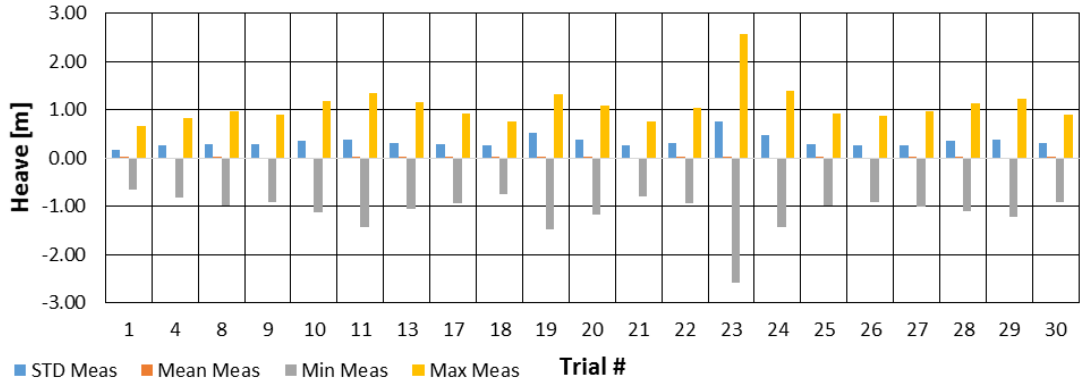


Figure 9: Heave motion for station-keeping trials

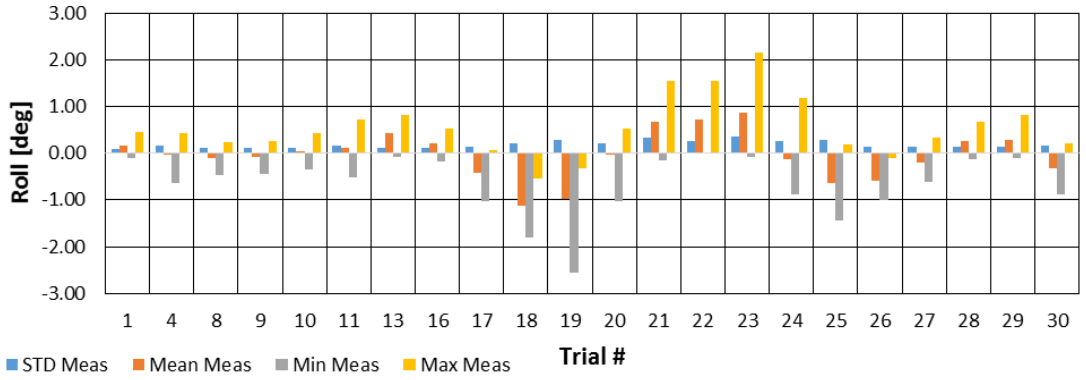


Figure 10: Roll motion for station-keeping trials

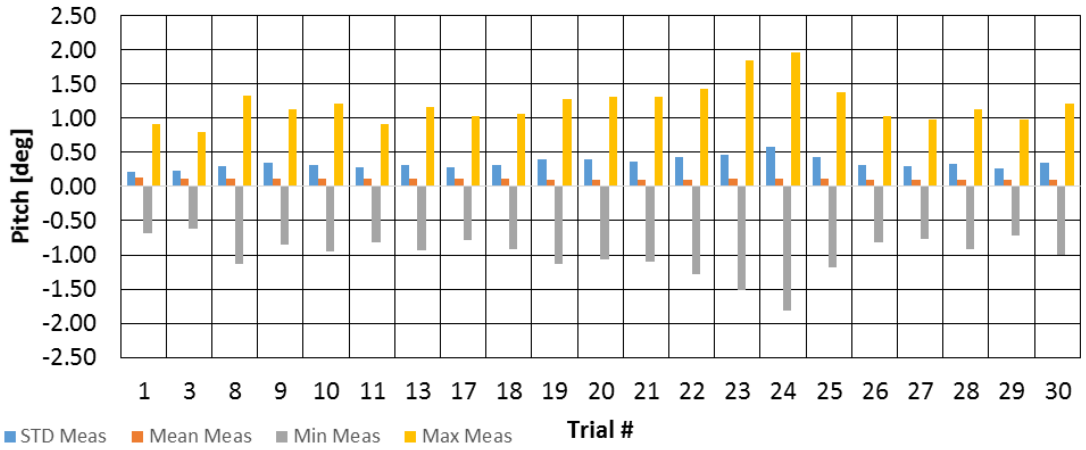


Figure 11: Pitch motion for station-keeping trials

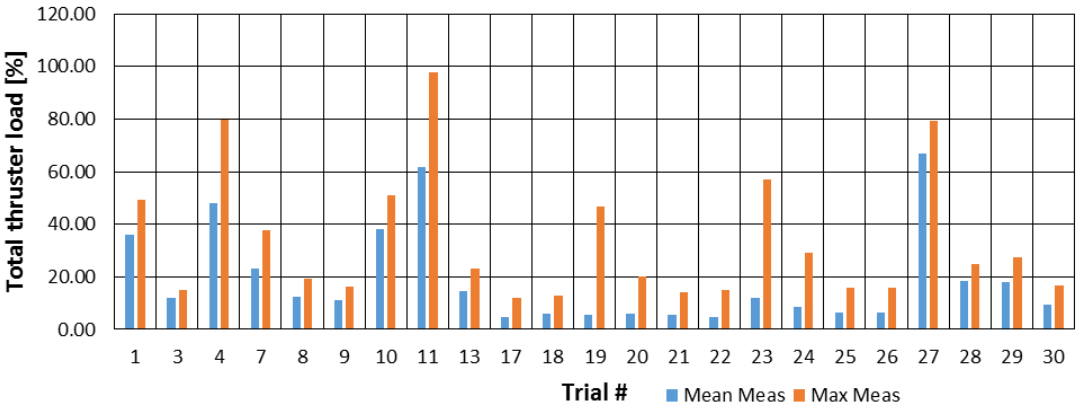


Figure 12: Average total thruster load for station-keeping trials

Trials with significant and sudden change of heading in DP

Three trials were carried out for evaluating the robustness of the station-keeping performance when performing a significant heading change. The results of this trials may reveal important operational aspects. The vessel station-keeping performance may be known for the heading at the beginning and at the end of the manoeuvre (by looking at realistic DP Capability analyses) but the behaviour of the vessel during the heading change may not be easy to predict.

The first test (trial 2) was performed with weather initially attacking the stern of the vessel, and by changing the vessel heading to face the current with the bow, see Figure 13 a). The second test (trial 12) was performed from facing the weather with the bow to facing the weather with the stern, see Figure 13 b). The third manoeuvre (trial 14) was done to face the weather with the bow again, see Figure 13 c). For all three tests, the environmental condition were quite similar (H_s from 2.55 m to 2.8 m, Wind speed from 8.4 m/s to 13.3 m/s and current speed from 1.95 to 2.11 m/s).

All the heading changes were done in steps, where the first heading change was typically larger. In the first trial, time between heading changes was larger than for the other two tests, meaning the vessel was exposed to an unfavourable heading angle for longer time compared to the other two trials. Another difference in the tests was the desired rate of turn (in yaw) which was set to 10, 20, and 45 deg/min for each test respectively. This means the trials were performed increasing the vessel rotational speed. Also for the first test the DP control gains were set to *high* while for the other two trials the DP control gain settings were customized based on the current direction in order to minimize the drift off. The first test had the largest position excursion (466 m) and it took 31 min before regaining position. The second test resulted in a position excursion of about 161 m, taking 11 minutes to get back to position. The last test produced an excursion of 110 m, regaining position in 6 minutes.

It is clear from these tests that a faster rate of turn and higher DP control gains results on a smaller position excursion and smaller time to regain the position. This information could be of vital importance during a drilling operation where a large excursion may lead to the disconnection of the drilling riser.

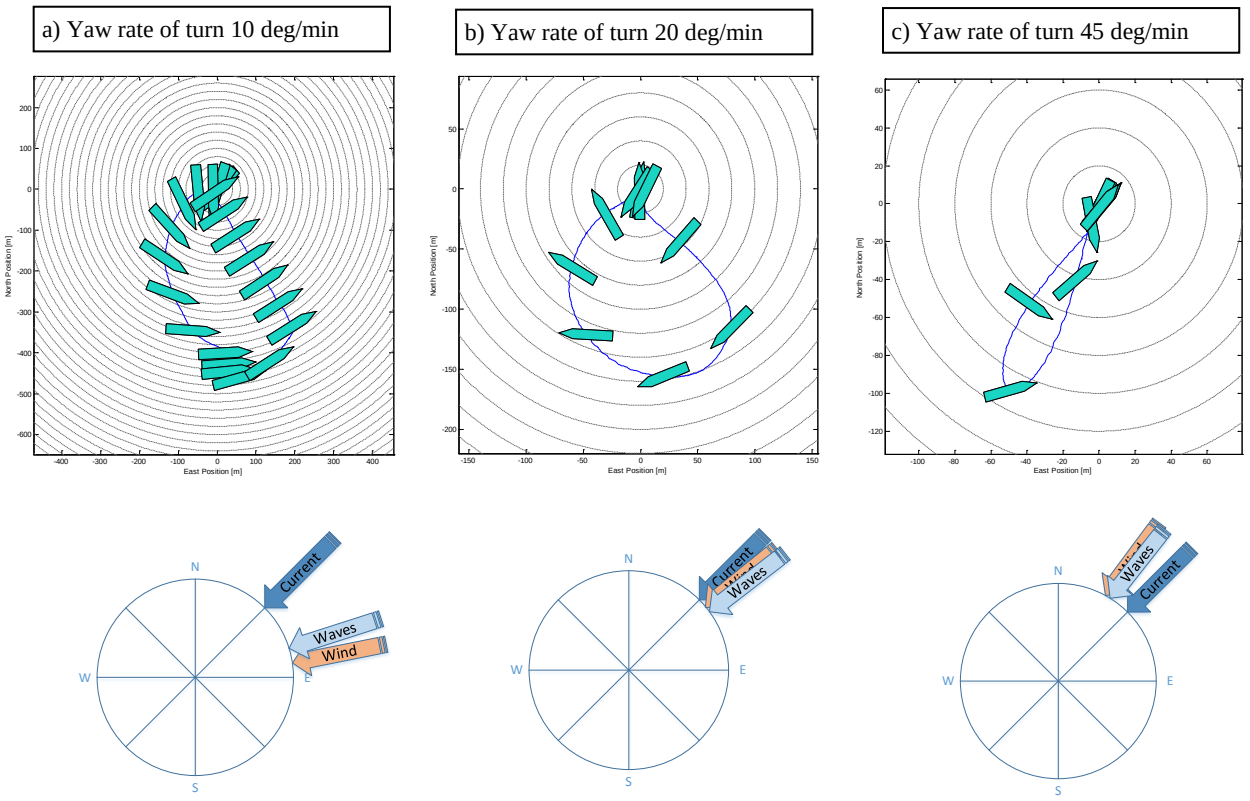


Figure 13:Vessel footprints for heading change maneuvering

Station-keeping in DP with thruster(s) failure

To trials were performed to evaluate the robustness of the DP station-keeping performance upon the worst single thruster failure and the worst case single failure. The first test (trial 5) was performed by disabling thruster 1 while the second test (trial 6) was done by disabling both thruster 1 and thruster 4. The thrusters were disabled after about 180 s from the test start. Both tests were performed in high current speed and moderate waves and winds with the vessel heading chosen to have the bow toward the prevailing environmental loads (optimal heading to minimize the environmental loads). The results from the two tests showed that the station-keeping performance was very good with a maximum position deviation from setpoint of about 3 m and heading deviation of 4 degrees, see Figure 14. In trial 5, the heading deviation was already around 4 degrees when the test started and its value did not vary much even after the failure.

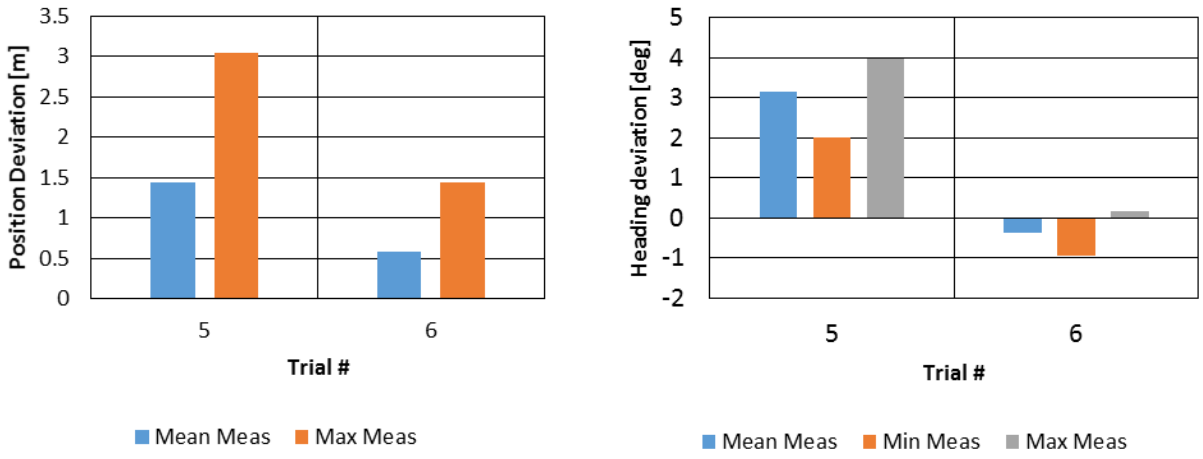


Figure 14: Position and heading deviation for the thruster failure trials

Time-domain simulations with DynCap

This section described the simulations performed for a comparison with the full-scale data. Simulations were executed with DynCap, a software tool developed by DNV GL Marine Cybernetics Services, based on CyberSea™ technology. DynCap employes a Vessel Simulator built and configured specifically for Maersk Venturer (a digital twin of the vessel tested).

Concept description

DynCap is based on systematic time-domain simulations with a complete 6 DOF closed loop vessel model. This includes dynamic wind and current loads, 1st and 2nd order wave loads including slowly-varying wave drift, as well as the dynamics of the propulsion system and power system. A model of the Power Management System (PMS) is also included to simulate relevant functionality for DP operations such as black-out prevention, load limitation and sharing, and auto-start and auto-stop of generators. To close the loop, a model of the full DP control system is included with observer (Kalman filter like), DP controller and thrust allocation, sensors, and position reference systems. The complete propulsion system model includes actuator rate limits and computation of dynamic thrust loss effects such as the interaction between thrusters, interaction between thrusters and hull, ventilation, out-of-water effects, and transversal losses based on empirical models. External loads from e.g. mooring lines, risers, hawsers and similar can easily be included in the analysis, including time-varying and motion dependent forces. More details on the vessel model can be found in [2], [4], [12], and in the references therein. The DynCap analysis can be performed for collinear environmental loads (wind, current and waves attacking from the same direction) or non-collinear loads, and any desired combination of wind, waves and current directions.

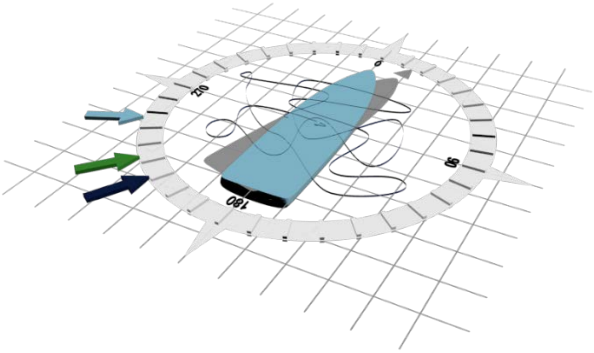


Figure 15: Vessel footprint from DynCap simulations

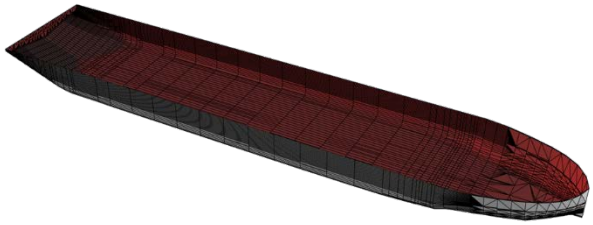


Figure 16: 3D hull geometry

One of the advantages of the DynCap simulations, compared to a traditional DP Capability analysis, is that the simulations are able to provide, among other vessel states, the vessel footprint (position and heading deviation from setpoint) which is not available in the traditional calculation, see Figure 15. Due to this, the limiting operating condition can be computed by applying a set of user defined acceptance criteria. The position and heading excursion limits can be set to allow a wide or narrow footprint, or the acceptance criteria can be based on other vessel performance characteristics such as sea keeping, motion of a crane tip or other critical point, dynamic power load, or tension and/or angle of a hawser or riser. In this way the acceptance criteria can be tailored to the requirements for each vessel and operation. This is important when calculating the vessel operability. Traditional operability studies are typically divided in two separate analyses: A quasi-static DP Capability study to investigate the station-keeping ability of the vessel in the design environmental conditions, and a sea-keeping analysis to investigate the wave-induced motion of the vessel, typically employing the motion Response Amplitude Operators (RAO's) of the vessel. The DP Capability study then focuses on the horizontal-plane motion (surge, sway, and yaw) and the ability to stay on position, whereas the sea-keeping analysis focuses on the vertical-plane motion (heave, roll, and pitch) and the limits this motion imposes on the desired operation. With DynCap, these two analyses can be combined in one, since the full 6DOF motion including wave-induced motion is simulated. The acceptance criteria may e.g. be a combination of station-keeping limits (watch circle) and heave/roll/pitch motion. Example of application of DynCap simulations can be found in [1][2][3][5][12].
The simulations presented in this paper are based on Level 3-Site in the new DNV GL ST-0111 standard for the assessment of the DP station-keeping capability [8].

Validation approach

The Vessel model has been built from vessel specific data such as thruster characteristics, power single line diagram, general arrangement (GA) drawing, load condition report, etc. The hydrodynamic coefficients such as added mass, potential damping, hydrostatic coefficients, and 1st and 2nd-order wave load coefficients are computed using WAMIT [6]. The input to the program is a 3D geometry file represented by panels, as shown in Figure 16. Wind and current drag models were obtained from computational fluid dynamics (CFD) calculations. All dynamic thrust losses due to Coanda effect, inline and transverse water velocity, thruster interaction, and propeller aeration[1] losses were modelled based on empirical methods derived from model-scale experiments, see [13] and [14] for more details. The simulation results presented in this article were obtained without further simulator tuning after the sea trials. This is planned to be the next step in this project.

Validation results

The comparison between simulated results and full-scale data was performed by running 30 minutes long time-domain simulations employing 5 different wave random seeds for obtaining 5 different wave realizations[2]. Figure 17 and Figure 18 show the comparison of the maximum values of position and heading deviation from setpoint. The trials compared were selected based among the ones that had a stable position and heading at the beginning of the test in order to have a fair comparison with the simulations (which always start with a stable position and heading).
From the comparison it can be seen that the results are fairly good. The accuracy of the simulated heading deviation from setpoint is slightly worse than the accuracy of the simulated position deviation. There are many factors that can affect the results from simulations. The readers is referred to [3][5][12], where a detailed description of these elements is provided. There are uncertainties in the estimation of the actual environmental conditions during the full-scale trials and the measurements obtained during the trials. Although the ocean current forecast presented quite stable predictions, current speed and direction were measured only at the beginning of each day and these conditions may have changed slightly during the day. Also the current speed was obtained from the measured one (49 m deep) by adding a 5%. The wave direction was estimated by crew observations.

[1] Propeller aeration (or ventilation) is due to the propeller being closed to (or piercing) the water surface and is the result of air or exhaust gases being pulled into the propeller blades.
[2] The wave elevation observed in the oceans changes randomly in time and it is not repeatable in time and space. Theory has shown that waves in deep water can be modelled as Gaussian random processes. This means that waves with the same stochastic description will produce different wave elevations in time. As the statistical parameters of the ocean changes much more slowly than the wave elevation it can be assumed that the wave elevation process is stationary over a short time, typically taken to be three hours.

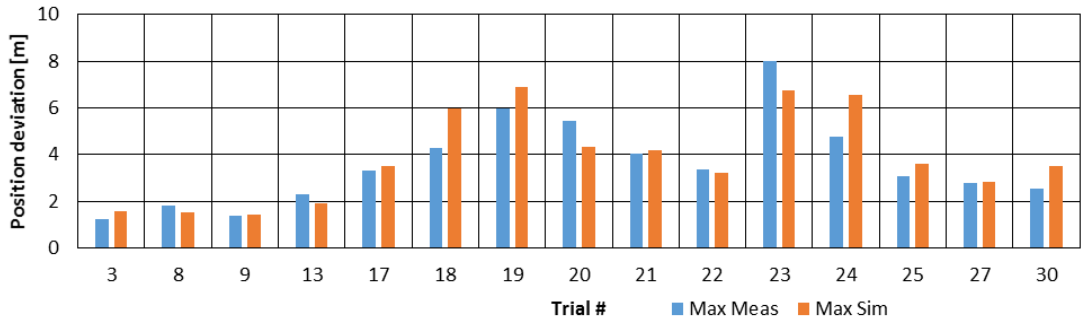


Figure 17: Position deviation for station-keeping trials – Comparison between measurements and simulations

Secondly, there are uncertainties in the DynCap vessel and equipment models. Thirdly, there will be discrepancies between the DP system and the DP system model, encompassing DP controller, observer and thrust allocation. Fourthly, obtaining statistically significant results requires that the measurement are taken for a sufficiently long time. This is especially important when the extreme results are of key interest. A commonly used time span is to simulate 3 hours for a given environmental condition [7]. Running 3h-long trials was not practically possible thus the comparison has to be performed for shorter time windows instead as the length of each trial was around 30 minutes. In addition, not all the trials started with the DP control system in a stable condition where either the position deviation or the heading deviation from the setpoint were still converging toward zero. Waiting for the DP control system to fully stabilize for each trial would have taken more time and it was not practically possible. The simulations were always logged starting from a stable controller condition. All of the above means that a perfect match between the full-scale trials and the simulations cannot be expected. However, a reasonable match and the correct trends were achieved.

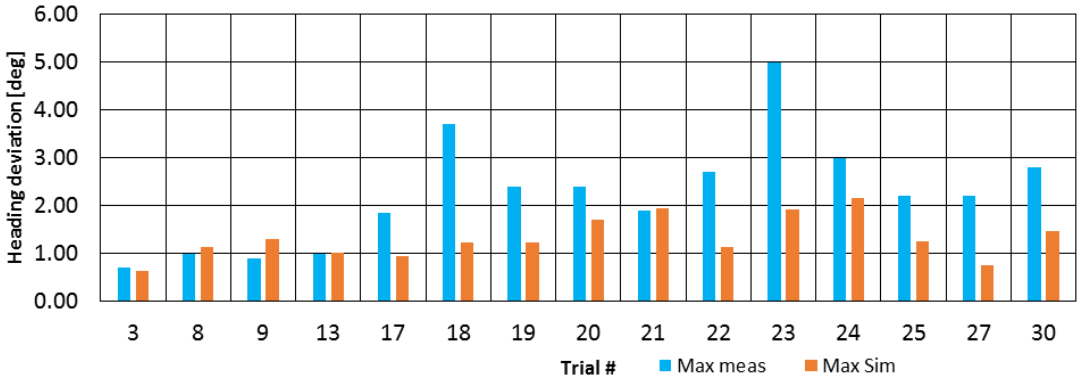


Figure 18: Heading deviation for station-keeping trials – Comparison between measurements and simulations

Figure 19, Figure 20 and Figure 21 compare heave, roll and pitch maximum motions from the trials and simulations. The difference in heave, besides for trial 30 where the difference was about 1 m, was always within 60 cm. The simulation results for the maximum roll and pitch angles compare well with the measurements, where the difference is always smaller than 1 degree.

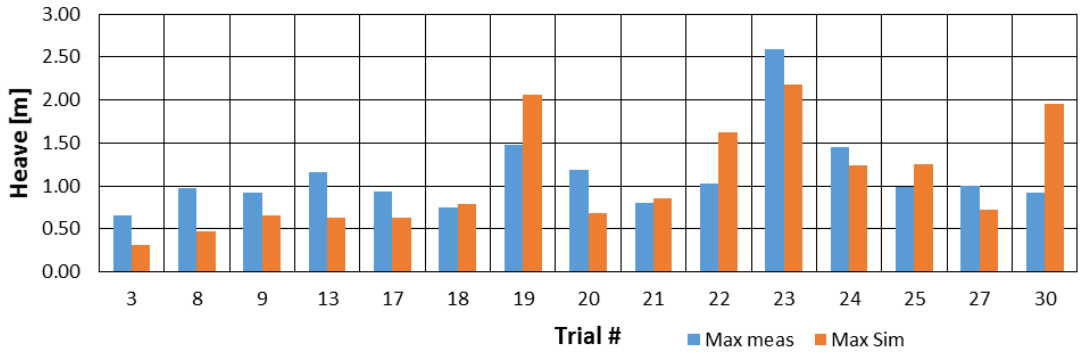


Figure 19: Heave motion for station-keeping trials – Comparison between measurements and simulations

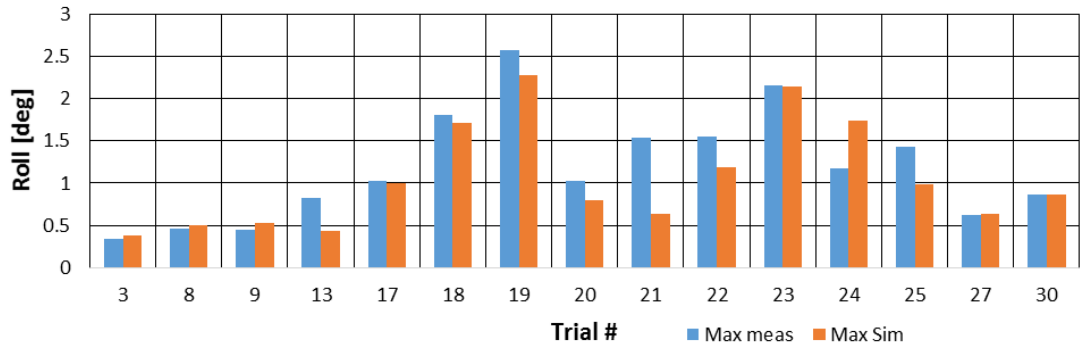


Figure 20: Roll motion for station-keeping trials – Comparison between measurements and simulations

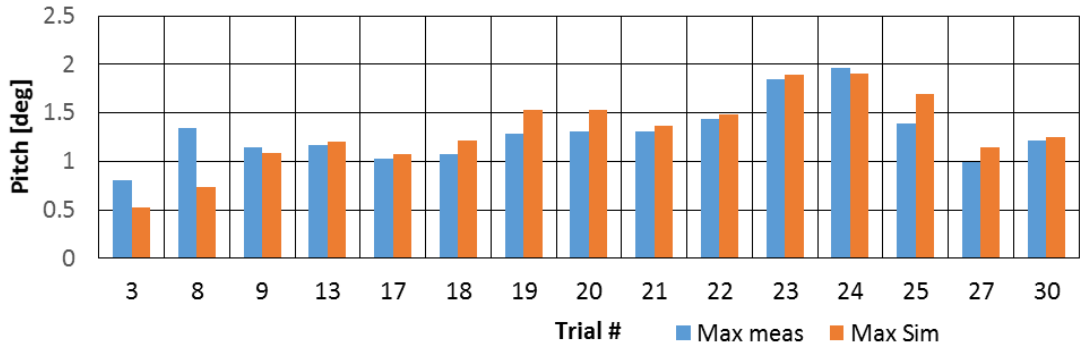


Figure 21: Pitch motion for station-keeping trials – Comparison between measurements and simulations

Figure 22 shows the total thruster power utilization from measurements and simulations. The mean values agree fairly well. When looking at the power maxima, there are few simulations which present larger maximum consumption. These are the trials from 18 to 30 which are the ones with the largest significant wave height. By looking at the time-series and environmental forces, simulations showed quite large waves which may not have been experienced during the trial. The significant wave height is a statistical property meaning that with the same H_s, one wave realization could have a larger highest wave than another realization. To have a full comparison, more trials should have been performed with the same environmental condition. This was unfortunately not practically achievable. An interesting case is trial 23 where the simulator power utilization is also larger than the measurements. Both the simulator and the real vessel seem to be at the limits of the vessel capability (max measured position deviation is 8 m and simulated 6.5 m). The simulator tries to regain position using more power than the real vessel

suggesting that the DP control gains adopted in the simulations may be higher (faster response) than in the actual vessel.

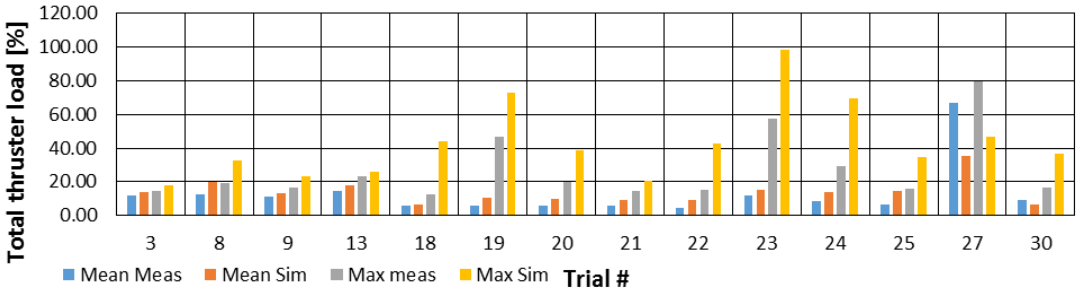


Figure 22: Average total thruster load for station-keeping trials – Comparison between measurements and simulations

Station-keeping in DP with thruster(s) failure

Trials 5 and 6, where thruster failures have been simulated, are compared to the results obtained with the simulator. Figure 23 shows the comparison of the maximum position deviation (left figure) and the maximum heading deviation (right figure). The position deviation shows quite good agreement between the simulation and the full-scale data. For trial 6 (loss of thruster 1 and 4), the maximum heading deviation from the simulation is very close to the measured data. For trial 5 (loss of thruster 1) the measured heading deviation was already around 4 degrees when the test started and it did not change much (see the heading standard deviation on the right figure). In this case the heading was not stable before the test started (it was still converging toward the setpoint). The standard deviation from the heading measurements and simulations matches well. Based on this it can be concluded that the simulation could have reproduced the full-scale data well if they had the same initial conditions. Figure 24 shows the vessel footprint (left figure) from simulations and measurements for trials 6. The right side of Figure 24 shows time series from the thruster power utilization from simulations and measured data. The thruster power utilization from simulations is smaller than the measurements. This could be due to the reasons and uncertainties described above. In this particular case, it could be that the thruster model underestimates the power usage at low load values. By looking at the increase of thruster utilization after the thruster failure, Figure 24 shows well that the active thrusters compensate for the two that were disabled.

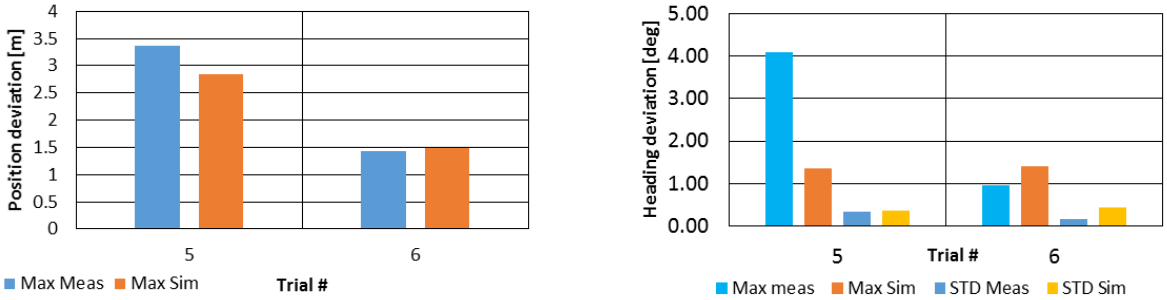


Figure 23: Position and heading deviation for the thruster failure trials – Simulations vs measurements

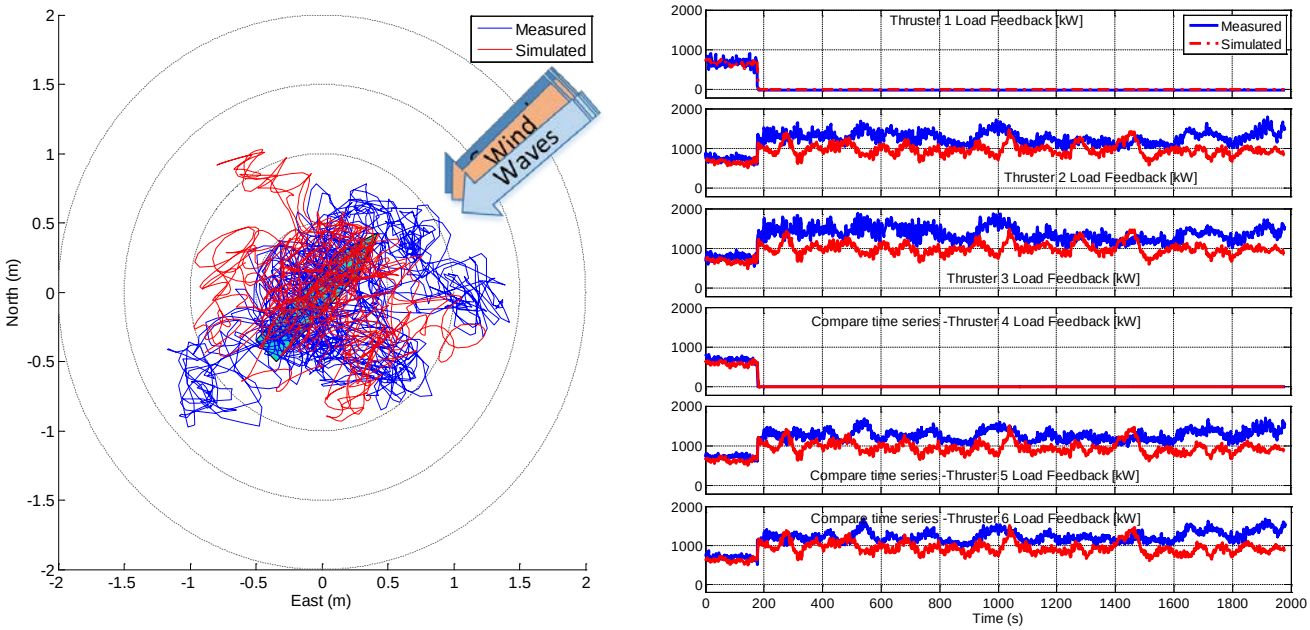


Figure 24: Vessel footprint (total vessel motion) and thruster loads from measurements and simulations for case 6

Conclusion

As oil and gas exploration is moving toward deepwater and further away from shore, extreme environmental conditions put new challenges on oil companies and operators. Both cost and risk increase, thus the need for gaining operational experience and for efficient planning tools is more important than ever.

The aim of this paper was to share experiences in planning DP drilling operations in a harsh environment dominated by extreme ocean currents. The paper first presented the full-scale trials performed with the drill ship Maersk Venturer, an enhanced Samsung Drilling V-class series drill ship belonging to Maersk, outside South Africa where the environmental conditions were particularly harsh, including high current speeds and large waves. Maersk Venturer is installed with an advanced Thruster and Engine control, which is governed by a specially designed Power Managements System, including fast blackout recovery and enhanced blackout prevention devices. This differentiates it from the standard series of Samsung drill ships, making the total DP system very robust and enhanced.

Based on the results and according to the vessel operator, for the trials performed in station-keeping condition (DP mode), the positioning performance was very good.

There has been an occasion where, due to a non-optimal heading positioning, the vessel experienced a position excursions of about 8 m. This was the largest position excursion recorded in the station-keeping tests. Heave, roll and pitch motions were also contained to small values for all tested conditions. Trials performed to compare the vessel performance with either the bow or the stern against the current direction, with current and waves acting on opposite directions, showed that the vessel station-keeping capability was comparable with no evident gains for either strategies.

Two trials were performed to test the station-keeping performance upon single thruster, and worst case single failure. In the tested conditions (H_s between 2.66 and 2.85 m, current speed 1.95 m/s), results showed that the positioning was not affected by the failures and contribute to gain confidence in the defined project operating limits for which the worst case failure was a critical aspect.

Three trials were carried out for evaluating the robustness of the station-keeping performance when performing a heading change. The trials showed that a faster rate of turn and optimal DP control gains resulted in a smaller position excursion and shorter time to regain position. This information could be of vital importance during a drilling operation where a large excursion may lead to the disconnection of the drilling riser.

The paper presented also a comparison between the full-scale trials and time-domain simulations performed with DynCap, a software tool developed by DNV GL Marine Cybernetics Services. Simulations were performed in station-keeping conditions and with thruster failures applying the same vessel and environmental conditions encountered during the trials. Despite the uncertainties on the models, environmental conditions and the length of

each trial (non-optimal for extreme motion evaluation), the results showed a reasonable match and the correct trends between the full-scale data and the simulations.
In conclusion, it has been demonstrated that DynCap is an important addition to other available tools, which gives unique insight into the details of a vessels station-keeping performance. We also believe the results have shown that DynCap simulations are comparable to full-scale measurements. When full-scale data are not available, DynCap could provide important results for understanding the vessel performance and limitations, in turn providing valuable input to operating guidelines, operational risk assessment and planning.

Acknowledgements

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