The Next Level DP Capability Analysis

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Abstract

The traditional DP Capability Analysis (DPCap) as described in IMCA M140 is the current industrial standard for analyzing a vessel’s station-keeping capability. These analyses are used for vessel design, charter agreements and operational planning.

A DPCap analysis is inherently quasi-static, meaning that all dynamic effects must either be neglected or handled by safety factors. Hence, the DPCap analysis can only balance the mean environmental forces with the mean thruster forces, and cannot account for e.g. the transient conditions during a failure and recovery after a failure.

Dynamic Capability (DynCap) is the next level DP capability analysis tool. DynCap is based on systematic time-domain simulations with a sophisticated 6 DOF vessel model, including dynamic wind and current loads, 1st and 2nd order wave loads with slowly-varying wave drift, a complete propulsion system including thrust losses, power system, sensors, and a DP control system model. Most of the limiting assumptions needed for the traditional DPCap analysis are removed, yielding results much closer to reality. It is also possible to tailor the acceptance criteria in the analysis to the requirements for each vessel and operation, such as station-keeping footprint, sea-keeping criteria, dynamic power load, and transient motion after failure.

This paper presents the DynCap analysis methodology and a comparison between the capability plots obtained with the traditional DPCap and the DynCap analysis methods for three different vessel designs. The paper also demonstrates how the DynCap methodology can be used in a fuel consumption and operability analysis as well as analyzing the transient motion after a failure, and finally presents a model-scale experimental verification of the concept.

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Introduction

In the last decade the number of DP vessels has increased dramatically driven by an increased offshore activity. Operations such as deep-water drilling, diving, subsea construction and maintenance, pipelaying, shuttle offloading, platform supply and flotels rely heavily on DP. For these operations, where the stakes are high both regarding cost and safety, it is essential to determine the weather operational window where the vessel can maintain its position and heading, typically also after a single failure. This is the aim of the DP capability analysis, which is extensively used by industry for vessel design, chartering agreements, operational planning and conduction of operations.

The importance of DP capability is steadily increasing as the industry is moving into harsher environments, and focus on risk management and HSE is increasing.

The current industrial standard for DP capability analysis is described in ISO 19901-7 and IMCA M140 [3], aiming to enable a direct comparison of individual vessel’s performance and provide an indication of station keeping capability in a common and understandable format. However, there are significant limitations in these standards, and the trustworthiness of the current capability analyses are often questioned; Are they conservative or non-conservative? Can they be compared? Do they convey a realistic picture of a vessel’s station-keeping capability in dynamic operating conditions?

The traditional DP capability analysis based on the IMCA M140 specification, here abbreviated as DPCap, is performed by statically balancing the maximum obtainable thruster force against a resultant mean environmental force due to wind, wave drift, current, and possible other loads. This is done for the full angle-of-attack envelope (0−360 deg). The results of such analyses are presented in form of polar plots termed wind envelopes, where the maximum wind speed at which the vessel can maintain position and heading is plotted for each angle of attack, typically given with 10-15 degree spacing. In addition, results may also be presented as thrust envelopes showing the thruster utilization for a given design condition at different wind angles of attack. Figure 5 and Figure 6 show examples of typical wind and thrust envelopes.

The IMCA M140 specification is quite basic allowing the analysis to be computed with environmental forces from non-vessel-specific coefficients, thruster forces from generic rules-of-thumb and without including specifications on DP control system and thrust allocation. It is possible to extend the analysis with more realistic assumptions and models. This can be done for example by using actual vessel model data such as wind, current, and wave-drift coefficients, realistic thruster models, and realistic static thrust allocation including e.g. forbidden zones and thrust loss effects based on actual allocated thrust. However, such extensions are not standardized.

One of the strongest assumptions in the traditional analysis is that the vessel is considered at rest. It is not possible to include the dynamic loads from waves, wind and current, and the corresponding dynamic response of the vessel with its DP system. Hence, the DPCap analysis can only balance the static (mean) environmental forces with the mean thruster forces, meaning that a certain (assumed) amount of thrust must be reserved to counteract the unknown dynamic forces and vessel motion. Typically 15%-20% of the thrust is reserved for dynamic loads. This is often referred to as dynamic allowance. Furthermore, the 6DOF vessel motion and the related thrust losses, as well as all other dynamic effects in the propulsion system like rate limits are usually neglected.

The fact that the IMCA M140 specification presents relaxed requirements and that the analysis can be computed employing disparate methods makes the comparison of the DP capability between different vessels difficult. Furthermore it is not straightforward to assess how realistic the results from the analysis are compared to the actual performance.
Another significant shortcoming of the quasi-static DPCap analysis is that it cannot account for the transient conditions during a failure and recovery after a failure. Even if the quasi-static capability plots show that the vessel can maintain position and heading both in intact condition and after a single failure, nothing can be said about the motion of the vessel from the time the failure occurs until the desired position and heading has been regained. Especially after a worst case single failure for a DP2 or DP3 vessel, where as much as half of the thrust capacity may be lost, re-allocation of thrust can take significant time due to limitations in rise time for propellers as well as rudder and azimuth angle rates. For a safety-critical DP operation such as diving or vessel-to-vessel replenishment or personnel transfer, the allowance for such transient motion can be very limited.

An example of the difference between the theoretical and actual capability is provided in [5]. In this paper the full-scale measured DP capability was dramatically different from the theoretical one after the worst case single failure, likely due to large interaction between the thrusters and the rig structure. This shows that in order to obtain results comparable to the actual vessel performance, modelling of the vessel dynamics and especially thruster-thruster and thruster-hull interactions must be accurate.

This paper introduces the next level DP capability analysis tool coined DynCap: Dynamic Capability. DynCap is based on systematic time-domain simulations with a complete 6 DOF vessel model, including dynamic wind and current loads, 1st and 2nd order wave loads including slowly-varying wave drift, a complete propulsion system including thrust losses, a power system, sensors, and a DP control system with observer, DP controller, and thrust allocation. By considering the complete vessel, environmental forces, and control system dynamics, most of the assumptions needed for the traditional DPCap analysis are removed, yielding results much closer to reality.

The outline of the paper is as follows: The next section presents the closed-loop vessel simulator used in the DynCap analysis, followed by a section describing the DynCap concept. The following four sections present an overview of the case studies and the comparison results for a supply vessel, a shuttle tanker and a semisub. Thereafter, an example of a fuel consumption and operability analysis is presented, followed by an example of the transient motion after a worst case single failure for the shuttle tanker. The paper is finalized by a schematic comparison of the DynCap and DPCap concepts and a conclusion.

The closed-loop vessel simulator

DynCap is based on systematic time-domain simulations with a complete 6 DOF closed loop vessel model. A block diagram describing the vessel simulator is shown in Figure 1. By allowing the vessel to move, the strongest assumption for the traditional DPCap analysis is removed. This facilitates inclusion of 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 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 model is included with observer (Kalman filter), 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. More details on the vessel model can be found in [4].

By considering the vessel, environmental loads and DP system dynamics, it is not necessary to reserve a certain amount of thrust for dynamic loads as for the traditional DPCap analysis. DynCap utilizes all the available thrust capacity like the vessel would do in real life. In addition, the DP system model includes
functions that can be found in the majority of DP control systems available today, such as black-out prevention and load limitation. If the required power for maintaining position and heading exceeds a preset limit, the thruster loads are limited such that those limits are not passed.

**Figure 1: Closed-loop time-domain vessel simulator**

**The Dynamic Capability Concept**

The main purpose of the DynCap analysis is to calculate the station-keeping capability of a vessel based on systematic time-domain simulations. The station-keeping capacity is calculated by searching for an environment limit at which the vessel is still able to satisfy a set of user defined acceptance criteria. In the IMCA specification for DP capability ([3]), the acceptance criterion is being able to keep the position and heading. The analysis can be performed for collinear environmental loads (wind, current and waves attacking from the same direction) or non-collinear loads.

The analysis is typically performed for intact condition where all the equipment is available and for the worst case single failure (WCSF) condition. In addition the analysis can be run with any thruster and power setup to evaluate the station-keeping capability when not all the equipment is available (for example due to maintenance).

One of the advantages of the DynCap analysis, compared to a traditional DPCap, is that the limiting environment 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. An example of position and heading acceptance criteria is shown in Figure 2. In this case, the station-keeping capacity is found by searching for the maximum wind speed in which the vessel footprint stays within the predefined position and heading limits.
By considering the complete vessel dynamics it is also possible to identify temporary position and/or heading excursions due to dynamic and transient effects. As an example, a vessel may stay in position without one thruster according to the traditional DPCap, but the loss of that thruster during station-keeping may cause a temporary excursion outside the positioning acceptance limits.

During DP operation, the vessel position and heading motion is characterized by two components:

- The motion displayed on a DP screen is checked towards positioning limits in the DP (watch circles). This is a filtered, low-frequency motion, which is due to the mean wave drift, thruster, wind and current forces. In literature, this is also referred to as the low-frequency (LF) motion.
- The harmonic (wave) motion due to first-order wave loads, which is oscillating about the LF motion. In literature, this is also referred to as the wave frequency (WF) motion.

The actual motion of the vessel is the sum of these two components; see Figure 3 for an example. Depending on the requirements to the operation, either the LF motion or the total vessel motion (LF+WF motion) can be used to check if the position acceptance criteria are satisfied in the DynCap analysis.

The DynCap results can be provided in various formats depending on purpose and simulation setup:

- Wind envelopes, directly comparable to the results obtained with a traditional DPCap study.
- Thrust envelopes, directly comparable to results obtained with a traditional DPCap study.
- Yearly operability at a given location, based on metocean data
- Yearly fuel consumption
Case Study Overview

In next sections, comparisons between DPCap and DynCap wind and thrust envelopes are presented as case studies. Three types of vessel with varying hull shapes, displacement and propulsion configuration are considered: a typical supply vessel, a typical shuttle tanker and a typical drilling semisub. The main particulars of the vessels are described in Table 1.

The hydrodynamic coefficients such as added mass, potential damping, hydrostatic coefficients, and 1st and 2nd-order wave load coefficients are computed using WAMIT [7]. WAMIT is a 3D potential theory computer program capable of analyzing wave interactions with offshore platforms and other structures or vessels. The input to the program is a 3D geometry file represented by panels, as shown in Figure 4.

The waves in this analysis are simulated using a JONSWAP wave spectrum with peak parameter $\gamma = 3.3$ and spreading factor $s = 1$ as recommended by DNV [1]. The wind-wave relationship is adopted from the North Sea data in IMCA M140 [3]. The environmental loads are set as collinear (wind, current and waves have the same direction). The power system operational philosophy is two-split switchboard. Results are shown for intact and Worst Case Single Failure (WCSF) conditions, WCSF being loss of one switchboard.
Table 1: Vessel main particulars

<table>
<thead>
<tr>
<th></th>
<th>Supply vessel</th>
<th>Shuttle tanker</th>
<th>Drilling semisub</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars</td>
<td>80.0 m</td>
<td>270.0 m</td>
<td>120.0 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>20.0 m</td>
<td>50.0 m</td>
<td>80.0 m</td>
</tr>
<tr>
<td>Draught</td>
<td>7.0 m</td>
<td>16.0 m</td>
<td>23.0 m</td>
</tr>
<tr>
<td>Displacement</td>
<td>7500 tons</td>
<td>170000 tons</td>
<td>55000 tons</td>
</tr>
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</table>

Propulsion system

<table>
<thead>
<tr>
<th>Thruster 1: type bollard pull</th>
<th>Bow tunnel 1:</th>
<th>Bow tunnel 1:</th>
<th>Fore stbd azimuth:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 kN</td>
<td>470 kN</td>
<td>1000 kN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thruster 2: type bollard pull</th>
<th>Bow azimuth:</th>
<th>Bow tunnel 2:</th>
<th>Mid stbd azimuth:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 kN</td>
<td>470 kN</td>
<td>1000 kN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thruster 3: type bollard pull</th>
<th>Main azimuth port:</th>
<th>Bow azimuth:</th>
<th>Aft stbd azimuth:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>280 kN</td>
<td>540 kN</td>
<td>1000 kN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thruster 4: type bollard pull</th>
<th>Main azimuth stbd:</th>
<th>Stern azimuth:</th>
<th>Aft port azimuth:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>280 kN</td>
<td>540 kN</td>
<td>1000 kN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thruster 5: type bollard pull</th>
<th>-</th>
<th>Stern tunnel:</th>
<th>Mid port azimuth:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>280 kN</td>
<td>1000 kN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thruster 6: type bollard pull</th>
<th>-</th>
<th>Main propeller:</th>
<th>Fore port azimuth:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1800 kN</td>
<td>1000 kN</td>
</tr>
</tbody>
</table>

The DP system model used in the simulations is configured and tuned according to industrial standards. It includes an observer to estimate position and velocity with performance comparable to a standard Kalman filter. The DP controller is chosen as a nonlinear PID-controller with wind feed-forward action. The DP gain has been tuned such that the DP vessel in closed loop acts as a mass-spring-damper system with undamped natural periods and relative damping ratios as specified in Table 2. The thrust allocation is implemented such that the azimuth thrusters are free to rotate.

Table 2: DP gain settings

<table>
<thead>
<tr>
<th></th>
<th>Undamped period</th>
<th>Relative damping ratio</th>
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</thead>
<tbody>
<tr>
<td>Surge</td>
<td>100 s</td>
<td>0.7</td>
</tr>
<tr>
<td>Sway</td>
<td>140 s</td>
<td>0.7</td>
</tr>
<tr>
<td>Yaw</td>
<td>140 s</td>
<td>0.7</td>
</tr>
</tbody>
</table>
For the DynCap analysis, the following choices have been made:
- All dynamic thrust losses are included
- The wind and current magnitudes are modeled by considering an average speed and a random effect (wind gusts and current fluctuations). For simplicity the current speed is set to 0.0 m/s.
- The low-frequency LF motion (see Figure 3) is used to check whether the vessel is able to stay within position and heading limits.

For the DPCap analyses, two cases are included:
- DPCap case 1: 0% dynamic allowance (no thrust reserved for dynamic effects), no thrust loss
- DPCap case 2: 20% dynamic allowance, with static thrust loss effects

DPCap case 1 is the basic analysis according to IMCA M140, although still with accurate model data (no rules-of-thumb) and proper static thrust allocation. Case 2 introduces more realistic assumptions, accounting for dynamic effects with a fixed safety factor (dynamic allowance) and static thrust loss effects, and may be considered a "high-fidelity" quasi-static DPCap.

For the DynCap analyses, three cases are included, defined by varying position and heading acceptance limits:
- DynCap case 1: position and heading limits: 5 meters and 3 degrees, respectively
- DynCap case 2: position and heading limits: 10 meters and 5 degrees, respectively
- DynCap case 3: position and heading limits: 20 meters and 10 degrees, respectively

For the thrust envelopes, the design condition is collinear:
- Wind speed = 20 m/s
- Significant wave height $H_s = 7.3$ m, wave peak period = 12.6 s
- Current speed = 0.0 m/s

The results for the thrust envelopes are shown for 4 of the cases: DPCap case 1 and the three DynCap cases.

Comparison study 1 – Supply Vessel

Figure 5 shows the 5 wind envelope cases for the supply vessel, for both intact and WCSF conditions. The DPCap with 0% dynamic allowance yields the maximum wind envelope; and the one with 20% dynamic allowance and thrust losses as expected results in smaller wind envelope. The environment limits from the DPCap analysis appear unrealistic with 55 to 65 m/s wind speed for head seas in intact condition.

The DynCap results appear more realistic with 30 to 40 m/s wind speed for head sea. As expected the wind envelope shrinks with increasingly strict acceptance criteria, however even the widest acceptance criteria (20 m / 20 deg) yield a smaller envelope than the DPCap with 20% dynamic allowance and thrust losses in head seas. The difference may be due to the small mass of the vessel; hence the motion is highly affected by the dynamic environmental loads.

Figure 6 shows 4 thrust envelope cases for the supply vessel, for both intact and WCSF conditions, using the same scale in both figures. A thrust envelope shows the DP capability in terms of the thrust utilization which is the ratio between the required average thrust to keep position in the design sea state and the maximum available thrust. The thrust utilization is calculated with a set of environmental attacking angles (here with a resolution of 10 deg) and presented in a polar plot. A thrust utilization less than or equal to 100% means that the vessel is able to keep the position. If the thrust utilization is not shown in an
environmental attacking angle, the vessel is not able to keep the position in that direction. Figure 6 indicates that the vessel is able to keep the position from the DPCap analysis for both intact and WCSF condition in all environmental attacking angles. However, the DynCap analysis shows that the vessel might not be able to keep the position in some environmental angles depending on the position/heading acceptance criteria. Figure 7, which is a zoom-in of the thrust envelopes in Figure 6, shows that the vessel is able to stay within 5m position radius and 5deg heading limits in head seas environmental directions of ±30deg for intact and of ±10deg for WCSF. If the acceptance limits are increased to 10m and 10deg, the vessel can keep the position within environmental directions of ±50deg for intact and of ±10deg for WCSF condition. It should also be noted that the thrust utilizations from the DynCap analysis are higher than from the DPCap.

For illustrational purposes, the vessel station-keeping performance in two simulation cases has been included. The two cases are indicated by arrows in Figure 5 and correspond to environment attacking angles of 10deg and 90deg for the DynCap wind envelope with acceptance limit of 5m/5deg. The time series show the vessel station-keeping performance in the simulation case where the wind speed is slightly above the highest speed where the acceptance limits are met. The results are shown in Figure 8 and Figure 9 in terms of the LF position trace together with footprint and the time series of LF distance from setpoint and LF heading. The footprint plots also include the position acceptance limits.

The time series (Figure 8 and Figure 9) indicate that the supply vessel does not meet the acceptance criteria because the both LF position and LF heading limits are breached.

*Figure 5: Wind envelopes for intact and WCSF for the supply vessel. The red arrows indicate two simulation scenarios that are studied closer in the following.*
Figure 6: Thrust envelopes for intact and WCSF for the supply vessel

Figure 7: Zoom-in of thrust envelopes for intact and WCSF for the supply vessel
Figure 8: Vessel performance in environment condition above limit, attacking angle = 10 deg

Figure 9: Vessel performance in environment condition above limit, attacking angle = 90 deg
Comparison study 2 – Shuttle Tanker

Figure 10 shows the 5 wind envelope cases for the shuttle tanker, for both intact and WCSF conditions. The results show a similar tendency as the supply vessel case. There is a notable difference between the DPCap and DynCap results. The difference may be due to high thrust loss from the main propeller. In general the DynCap result is closer to DPCap one if the acceptance limits are relaxed (widened).

Figure 11 shows 4 thrust envelope cases for the shuttle tanker, for both intact and WCSF conditions, using the same scale in both figures. The DPCap thrust envelope shows that the vessel is able to keep the position if the environment attacks between ±70deg head sea in intact condition and -30 to 20deg head sea in WCSF. However, the DynCap analysis shows that this angle window is narrower. For example, with acceptance limits 20m position radius and 10deg heading limit, the vessel can maintain position only if the environment attacks between ±30deg head sea in intact condition and from -20 to 10deg head sea in WCSF. If the acceptance limits are stricter, e.g. 5m/3deg, this angle window is even narrower.

Figure 10: Wind envelopes for intact and WCSF for the shuttle tanker
Figure 11: Thrust envelopes for intact and WCSF for the shuttle tanker

Comparison study 3 – Semisub
Figure 12 and Figure 13 show the wind and thrust envelopes, respectively, of the semisub. The results show that the differences between DPCap and DynCap, and between DynCap with different acceptance limits, are not pronounced. This can be explained as follows:

- Wind speed limit is around 30 m/s and 20 m/s for intact and WCSF, respectively.
- The wind speed of 20 m/s corresponds to significant wave height of 7.3 m and wave peak period of 12.6 s (IMCA M140 [3]).
- The wind speed of 30 m/s corresponds to significant wave height of 12.5 m and wave peak period of 16.6 s (IMCA M140 [3]).
- For the sea state with wave peak period higher than 12 s, the contribution from wave-drift load is not pronounced. The slowly-varying wave-drift load is the highest contribution to the dynamic motion of the vessel in surge, sway and yaw. Therefore, the difference between DPCap and DynCap results is not pronounced.
- Additionally, since the azimuth thrusters of the semisub are deeply submerged and not subject to dynamic thrust losses from ventilation and wave-induced velocities, the thrusters will give close to nominal thrust (i.e. zero thrust loss), further decreasing the differences between the analysis methods.

The results show that DPCap for the semisub with 20% dynamic allowance and thrust losses results in the smallest wind speed envelope. This is not the same tendency as compared to the shuttle tanker and supply vessel cases due to a different character of thrust loss as mentioned above. This indicates that the dynamic allowance of 20% might be high for the semisub.
Fuel consumption and operability study

Since the DynCap analysis is based on time-domain simulation, an additional application is to study the operability based on operational specific acceptance criteria and the fuel consumption during DP operation. With a complete power system model including consumers, switchboards and generators, the...
dynamic power demand is known. This can be combined with diesel engine fuel curves to give the instantaneous fuel consumption of all diesels, and integrated over time to give the fuel consumption per hour or day.

Combined with an operability study, this approach can be extended to evaluate the vessel yearly fuel consumption. The method is shown in the flow chart in Figure 14, and can be summarized as follows:

- The scatter diagram from the metocean data is discretized to a finite number of sea state conditions to capture the main environmental characteristics of the location.
- DynCap simulations are carried out in a specified sea state. In this phase, all vessel performance parameters in terms of positioning, generator performance, fuel consumption, emission, etc. are recorded.
- Simulation results are post processed: the vessel's station-keeping capability is checked against the operational limits (e.g. position and heading acceptance limits). If these criteria are met, the fuel consumption, CO₂ and NOₓ emissions are calculated. Contrarily, if the criteria are not met, the results will not be taken into consideration, meaning that the results will only account for the time where the vessel performance is satisfied.

$$\text{Operability} = \sum_{i=1}^{N=25} p_i \delta_i = 96\%$$

where $N$ is the total number of sea states, $i$ is the index of sea state, $p_i$ is the probability of the $i$th sea state, $\delta_i$ states whether the vessel satisfies the operational criteria.

Combined with this operability analysis, the yearly fuel consumption is calculated and given in Figure 15. The purpose is to compare the fuel consumption and emission of the vessel during DP operations.
employing different power setups as shown in Table 4. The fuel consumption analysis results shown in Figure 15 will aid the designer and the operator to choose the optimal power setup.

Table 3: Example of DynCap simulations for operability

<table>
<thead>
<tr>
<th>Sea state</th>
<th>Probability $p_i$</th>
<th>Significant wave height (m)</th>
<th>Peak wave period (s)</th>
<th>Current velocity (m/s)</th>
<th>Operation OK $\delta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.008</td>
<td>5.7</td>
<td>10.1</td>
<td>0.75</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>0.014</td>
<td>4.5</td>
<td>9.1</td>
<td>0.65</td>
<td>Yes</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>N = 25</td>
<td>0.018</td>
<td>0.5</td>
<td>5.2</td>
<td>0.25</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 4: Power setups used in fuel consumption analysis

<table>
<thead>
<tr>
<th>Setup</th>
<th>Class</th>
<th>Bus setup</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DYNPOS AUTRO</td>
<td>split bus</td>
<td>one generator per bus (3 total)</td>
</tr>
<tr>
<td>2</td>
<td>DYNPOS AUTRO</td>
<td>closed bus</td>
<td>minimum 2 generators</td>
</tr>
<tr>
<td>3</td>
<td>DYNPOS ER</td>
<td>closed bus</td>
<td>minimum 2 generators</td>
</tr>
<tr>
<td>4</td>
<td>DYNPOS AUTRO</td>
<td>closed bus</td>
<td>minimum 3 generators</td>
</tr>
<tr>
<td>5</td>
<td>DYNPOS ER</td>
<td>closed bus</td>
<td>minimum 3 generators</td>
</tr>
</tbody>
</table>

Figure 15: Example of operability and yearly fuel consumption

Transient motion after a failure
A DP2 or DP3 vessel is designed with redundancy against any single failure during DP operation. This is achieved by means of redundant machinery, switchboards, thrusters, computers, networks, sensors, and other critical equipment. For any single failure, the vessel should be able to maintain station-keeping until the operation can be aborted in a controlled manner. It should therefore be essential to ensure that the vessel is actually able to maintain acceptable position and heading even if the worst case single failure (WCSF) occurs – also during the transient period after the failure occurs. This transient period will be characterized by a temporary drift-off in position and/or heading while the DP system re-allocates thrust to the remaining thrusters, followed by a period of regaining position/heading before steady-state station-keeping is re-established (although with reduced performance, i.e. a wider foot-print). The magnitude of the temporary drift-off will depend on many factors, including the weather condition and the dynamic
characteristics of propellers and rudders. Especially important are limitations in propeller rise time as well as rudder and azimuth angle rates.

The conventional DPCap analysis can only analyze the steady-state station-keeping (which is then considered quasi-static). That is, for the WCSF analyses, the transient period from steady state DP operation in intact condition to steady state DP operation in WCSF condition cannot be included. These results are in reality only relevant for studying the station-keeping performance in a case where the operation is planned to take place in a degraded condition. If the operation is planned to take place in intact condition, and the capability analysis is used to evaluate the station-keeping performance in the case of a failure during operation, the transient period after the failure occurs is the most critical. It may then be considered a paradox that the prevailing industrial standard cannot account for such transients.

The DynCap case studies presented in the previous sections have all been performed in steady state DP operation after transients. This is convenient since it makes the results directly comparable to the DPCap analyses. However, the same limitations to the results regarding the transient period after a failure then apply as for the DPCap analysis. In this section the DynCap analysis is taken one step further, looking also at the transient period after the failure occurs.

Figure 16 shows an example of the vessel station-keeping performance in steady-state intact condition, during the transient condition from intact to WCSF, and in steady state station-keeping after WCSF. The results are for the shuttle tanker, with the environmental condition:

- Wind speed: 13.5 m/s
- Significant wave height: 4.5 m, wave peak period: 9.9 s
- Current speed: 0 m/s
- Collinear wind and wave attacking angle: 20 deg head sea

Figure 16a shows the footprint and position deviation for steady-state intact condition, with a maximum position/heading deviation of approximately 4 meters and 0.5 degrees. Figure 16c shows the footprint and position deviation for steady-state WCSF condition, with a maximum position/heading deviation of approximately 8 meters and 5 degrees. Figure 16b shows the transient period after the failure occurs, and in this period the maximum position/heading deviation is more than 20 meters and 5 degrees. The difference between the results in b and c is significant. For the shuttle tanker in the example, the result implies that the environmental condition for offloading may be chosen too high if only the steady-state conditions are considered.
Figure 16: Footprint and position deviation of the shuttle tanker before and after WCSF, including the transient period.
Model-scale Experimental Verification

An experimental verification of the differences between the traditional DPCap and DynCap analyses has been carried out employing a 1:30 scale model PSV type vessel design, CyberShip III, in the Marine Cybernetics Laboratory at the Norwegian University of Science and Technology (NTNU). CyberShip III is equipped with two electrically driven stern azimuth thrusters, and one electrical driven bow azimuth thruster. In order to compare the results with the model scale experiments, the analyses are carried out with the scaled vessel model. The results are then scaled back to full-size to ease the discussion and interpretation. This work is described in more detail in [1] and [6].

Figure 17 shows the wind envelope for CyberShip III, where the results from DPCap, DynCap and experimental data are included. The DynCap positioning acceptance criteria is 5m / 3degrees in full scale. In particular it is interesting to see that both plots obtained from DynCap and from the experiments have a dip at the 30, 60 and 90 degree angle. The fact that both the simulations and the experimental results have these unique characteristics is a strong indication of the accuracy of the DynCap analysis and the vessel model.

Investigating the differences between the DynCap results and the experimental results, we find that the relative difference between the plots is in average approximately 10%. Comparing DPCap with dynamics allowance and the experimental results, we find that the relative difference is much larger, approximately 60%. Investigating the time series from both experiments and simulations, it was found that for all headings, it is the heading deviation that is the limiting factor. Due to the motor dynamics and azimuth rate limits, the thrusters cannot produce force immediately on the wanted direction, thus limiting the vessel heading controllability.

Figure 17: DPCap and DynCap analysis compared to model-scale experimental data
Dynamic vs Static Capability, a summary

The main differences between the static DPCap analysis and the dynamic DynCap analysis are summarized in Table 5.

Table 5: Comparison of DPCap and DynCap

<table>
<thead>
<tr>
<th>Property</th>
<th>DPCap</th>
<th>DynCap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance between environmental and thruster forces</td>
<td>Static</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Dynamic environmental loads</td>
<td>Statistical considerations may be included</td>
<td>Included</td>
</tr>
<tr>
<td>Vessel position</td>
<td>Fixed: No dynamic vessel response</td>
<td>Free floating</td>
</tr>
<tr>
<td>Thruster capacity</td>
<td>Uses 80-85% of the thruster capacity - dynamic allowance of 15-20%</td>
<td>All available thruster capacity utilized</td>
</tr>
<tr>
<td>Thruster and rudder dynamics</td>
<td>Not included</td>
<td>Included</td>
</tr>
<tr>
<td>Thruster losses</td>
<td>Static losses may be included</td>
<td>Dynamic losses included</td>
</tr>
<tr>
<td>DP system</td>
<td>Dynamics of the DP system is not accounted for</td>
<td>DP controller, DP observer and thrust allocation included</td>
</tr>
<tr>
<td>External loads</td>
<td>Static may be included</td>
<td>Dynamic loads may be included</td>
</tr>
<tr>
<td>Transient effects</td>
<td>Not included</td>
<td>Included</td>
</tr>
<tr>
<td>Computational requirements</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Model complexity</td>
<td>Low to Medium</td>
<td>High</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Conclusion

Estimating the vessel station-keeping performance has been always a challenge for vessel design and operation. The traditional DP capability analysis as described in IMCA M140, which is the current industrial standard, has been shown to have significant shortcomings. Dynamic Capability (DynCap) analysis has been developed as a new method to give more accurate estimates of the station-keeping capability, employing systematic time-domain simulations with a sophisticated closed-loop vessel simulator. Most of the limiting assumptions needed for the traditional DPCap analysis were removed, yielding results that are expected to be much closer to reality. It was also possible to tailor the acceptance criteria in the analysis to the requirements for each vessel and operation, such as station-keeping footprint, sea-keeping criteria, dynamic power load, and transient motion after failure. Case studies with a supply vessel, a shuttle tanker, and a semisub have been presented to demonstrate differences between the analysis methods. Experimental data obtained with a model-scale supply vessel indicated that the DynCap results are significantly closer to the real station-keeping capability than the DPCap results.

The paper has also demonstrated further applications and advantages of the DynCap methodology, with examples of operability and fuel consumption studies as well as the analysis of the transient motion after a failure occurs.

Based upon the results presented in this paper, it can be concluded that if an accurate study of a vessels station-keeping capability is desired, the traditional DPCap may not be adequate. The simplifications and assumptions made when calculating the DPCap, according to the IMCA M140 specifications, result in wind and thrust envelopes which do not necessarily reflect the station-keeping capability of a vessel in a realistic manner. If the capability plot is to be used for determining the vessel operational window or to
select the right vessel for an operation, a more detailed standard based on time-domain simulations such as DynCap should be established.

References