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Dynamic positioning system capability analysis for offshore support vessel

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Abstract

The importance of Dynamic Positioning (DP) is growing because of the increase in the number of offshore construction sites requiring DP for their operations. The paper describes the background studies, methodology, and mechanism associated with the formulation and development of a reliable design tool to calculate DP capability, versatile enough to be integrated into the initial ship design stage of a vessel. The process includes the creation of the general concept of the solver module with the capacity to estimate empirically the external loads on the vessel due to the wind, current, and waves. The static force balance is obtained by suitably predicting thrust requirements for the propulsion system, bearing in mind the power and positional constraints. The optimization of the design variables for the station-keeping criteria targets the highest capability at the lowest possible energy expenditure. Finally, the results are automatically presented in the form of standard DP plots. As a method of cross-checking on the reliability, verification of the DP tool is done with the help of available data from DP offshore support vessel.

Keywords: Dynamic Positioning System; Offshore support vessel; Environmental forces; DP Capability plots; Azimuth thrusters; Static balance

Introduction

Dynamic positioning system (DPS) is defined by the International Maritime Organization (IMO) and the certifying class societies (DNV, ABS, LR, etc.) as the ability of a vessel to maintain desired position and heading in the presence of environmental disturbances from wind, waves, and current. This is done by using the thrust from installed propulsion and manoeuvring system to counteract the environmental forces acting on the ship [1].

Station keeping ability is used in different types of vessels with varying operational requirements. Cruise vessels and mega yachts use it in the form of virtual anchoring to avoid the environmental impact of anchoring in the sensitive estuaries they often ply. The importance of Dynamic Positioning system (DPS) is growing because of the increase in the number of offshore construction sites requiring DPS for their operations [2]. Over the last four decades dynamic positioning in deep water has been used in the marine sector, Oil and Gas industries, and military services in many tasks such as drilling, Oil and Gas floating production platform, cable and pipe laying, docking and towing, firefighting, supply, search and rescue, surveying, and mobile offshore bases (MOB). Each of these operations benefits from a DP system's ability to include precise position-keeping, freedom from the restrictions of mooring spread systems, the ability to move quickly from one site to another, and track-keeping capabilities [3].

Operation safety is always the first consideration in the design and operation of a Dynamic positioning system (DPS). To be able to plan a safe and efficient operation, it is important to know the maximum environmental conditions that DP vessel can withstand. During critical operations such as drilling, oil production and off-loading, the positioning precision requirements are high, regardless of the environmental conditions. It is thus important to know the positioning capability of the vessel which called Dynamic Positioning Capability (DPCap) in order to plan and execute operations in a safe manner [4].

DPCap analysis can assist in determining the maximum environmental forces that DP system can counteract for given headings. Mostly DPCap analysis investigates the dynamic positioning capability of the vessel from 0° to 360° headings. The environmental forces and moment are statically balanced by thrust forces and moment provided by the thrust system which consists of several kinds of thrusters. The positioning capability is determined by the maximum thrust of the thrusters as well as the optimized thruster configuration [5]. The aim of this paper is to study the offshore dynamic positioning system through application of DPCap analysis based on DNV-GL method. The main objective is to examine the maximum capability of DPS by estimating the highest wind speed that can be sustained using the optimized thruster configurations for a case study from offshore supply vessels. The accuracy and reliability of the DPCap analysis tool are validated by comparing with the results of a commercial DP Capability program introduced by Kongsberg.

Methodology

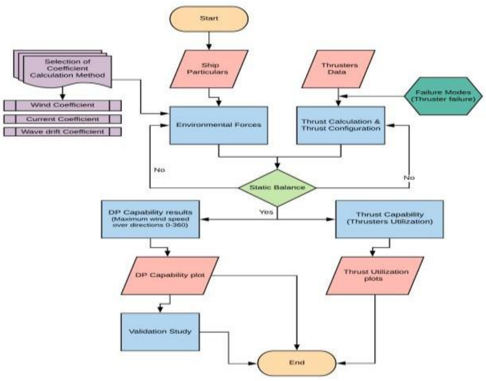
The flowchart in **Figure 1** represents basic working process selected for the DP capability analysis. The procedure of calculation must be methodological since several affecting factors are inter-related. Optimization process must deal with multiple loops over various sections and sub-sections before initiation of the next stages [7].

The flowchart starts with the input of the basic ship parameters, projected lateral and frontal areas, thruster's data which include power and positional data. The parameters related to the calculation of the environmental loads are constrained in terms of operational and interaction limits. The environmental force calculation combines the basic hull data, wind, current and wave coefficients to calculate the total surge, sway, and yaw loads on the vessel.

The coefficients are kept in the form of stored empirical, theoretical, or experimental data from where they are invoked according to the parameters and direction of the incident forces. All these datasets are used to calculate the static balance. The thruster outputs are varied within the range such that the surge, sway, and yaw moment they generate balances the incoming external loads.

In this paper, DP capability uses the concept of the static balance calculation to optimize the vessel's thrust scenario for the maximum wind speed that the vessel can handle for a particular direction of environmental forces. The optimization function, in this case, is the maximum sustainable wind using the minimum possible power input.

Figure 1. Structure of the DP capability analysis and optimization process



The technique of the static balance is used in the thrust capability calculations to estimate the thruster's utilization at one wind speed and one heading direction. The objective is to support the wind speed at minimum thrust requirements. The results are given in the form of thrust utilization plots.

All the above-discussed methods are combined in the DP capability estimation at variable wind as well as variable directions. The maximum points obtained are interpolated to get the DP capability plot.

The defined failure mode considering the failure of one thruster, or more is used to rerun the DP capability to present the failure plot.

The final step of the process is to make a validation study, the accuracy and reliability of the DP capability tool are tested. The DP capability plot considered as the backbone of the DP operations, is verified against standard commercial maritime computer program (StatCap program) which owned by The Kongsberg organisation.

A. Environmental loads estimation method

DNV-GL [10] recommends their own theoretical formulae for the estimation of the wind loads. The surge and sway coefficients can be determined by the recommended formulas below.

$$C_{WX} = -0.7\ \cos\alpha_W \quad (1)$$

$$C_{Wy} = 0.9\ \sin\alpha_W \quad (2)$$

DNV-GL [10] have their own empirical formulae to estimate directly the force (F_{CX}, F_{CY}) values as discussed in the following equations.

$$F_{CX} = \frac{1}{2}\rho_w \cdot V_c^2 \cdot B \cdot T \cdot (-0.07 * \cos\alpha_c) \quad (3)$$

$$F_{CY} = \frac{1}{2}\rho_w \cdot V_c^2 \cdot A_{L,current} \cdot (0.6 * \sin\alpha_c) \quad (4)$$

Where V_C is the current speed, $A_{L,current}$ is the longitudinal projected submerged current area, α_c is the current speed coming from direction, B is the maximum breadth at water line, T is the summer load line draft, and ρ_w is the water density (1026 kg/m^3) [11].

The estimation of the wave load for the ship takes two steps. In the first step, the corresponding wave height and crossing period are assessed from the tables indicating wind-wave correlations. Then these values are utilized with the respective coefficients to find the corresponding wave loads.

Only second order wave forces need be considered for DP capability. The first order forces are not counteracted by a DP system since these are high frequency and need not be considered. In producing capability plots [12] suggests that wave drift force coefficients can be scaled from data available on other vessels and [13] provides a set of regular wave drift force coefficients for a small mono-hull vessel.

B. Thrusters' forces estimation method

DNV-GL estimation of thrust for the transverse thrusters considers three efficiency factors. The first factor depends on the actuator properties, the second depends on the fairing of the inlet, and the third on the mechanical efficiency of the system. The available thrust force from an actuator shall be calculated as shown in Eq. (5) [14].

$$T_{eff} = T_{Nom} \cdot \beta_T \quad (5)$$

Where T_{eff}, T_{Nom} and β_T are the effective thrust, the nominal thrust and the thrust loss factor, respectively. The nominal thrust shall be calculated from the Eq. (6) [15].

$$T_{Nom} = K_1 \cdot K_2 \cdot (D \cdot P)^{2/3} \quad (6)$$

Where D is the propeller diameter constant and K_1 is constant regarding to the thruster type as shown in **Table 1**.

Table 1 Factor K1 values regarding to the thruster type

Thruster type	K_1
Azimuths, pods and shaft line propellers	800
Cycloidal actuators	900
Tunnel thrusters	900
Contra-rotating azimuths, pods and shaft line propellers	950
Ducted azimuths, pods and shaft line propellers	1200

$K_2$is constant related to the tunnel thruster type only as shown in **Table 2**.

Table 2 K2 value for tunnel thrusters

Tunnel shape	K_2
For broken inlets with α is (20,50) deg and b >	1
0.1 D	
For rounded inlet with r > 0.05 D	1.07
For all other inlet shapes	0.93

The K_2 factor for actuators other than tunnel thrusters is shown in **Table 3**.

Table 3 factor K2 for actuators other than tunnel thrusters

Thrust type	K_2
Forward thrust	1
Reversed thrust from FPP propellers without duct	0.9
Reversed thrust from FPP propellers with duct	0.7
Reversed thrust from CPP propellers without duct	0.65
Reversed thrust from CPP propellers with duct	0.5

P is the power applied to the propeller in kW which can be evaluated by Eq. (16).

$$P = P_B \eta_M \quad (7)$$

Where P_B is the maximum continuous rating brake power available in DP mode or bollard pull and η_M is the mechanical efficiency and its value related to thruster type as shown in **Table 4**.

Table 4 Mechanical efficiency regarding to thruster type

Thruster Type	η_M
Cycloidal actuators	0.91
Tunnel and azimuth thrusters	0.93
Permanent magnet actuators	1
Shaft line propellers	0.97
Pods	0.98

Case Study Description

The chosen supply vessel is already in operation with known DP characteristics. This ensures that the verification of the tool is not based on hypothetical methods, but on the authentic basis.

The "Pioneer" is a DP Class 2 ROV Subsea support vessel built by Jaya Asiatic Shipyard Batam Indonesia in 2011 and was previously known as the "IES Pioneer" and "Jaya Pioneer". The vessel is registered at Labuan, Malaysia and classed by DNVGL with DPS-2 notation. The principal dimensions are shown in **Table 5**.

Table 5 Principal dimensions of Pioneer vessel

Parameter	Value
Length Over All (L_{OA})	82.8 m
Length between perpendiculars (L_{BP})	81.9 m
Longitudinal distance between the foremost and aftmost points) LOS)	85 m
Breadth (B)	20.4 m
Depth (D)	7 m
Draught (T)	5.5 m
Displacement (Δ)	6324.6 t
Block Coefficient (C_b)	0.67

Table 6 Principal parameters for wind and current calculations

Parameter	Value	Unit
xL wind	9.3	m
xL current	1	m
Water plane midship areaa behind	800	m^2
AF wind	393.3	m^2
AL wind	907.8	m^2
AL current	500	m^2

The thruster and propulsion units consist of 3 x 680kW Kawasaki KT-88B3 controllable pitch bow tunnel thrusters, each are driven by 440V electric motors at 416 RPM. Bow Tunnel Thruster No.1 (T1) is fed from SG1 (440V Bus AA). Bow Tunnel Thruster No.2 (T2) is fed from SG2 (440V Bus BB). Bow Tunnel Thruster No.3 (T3) is fed from 440V Bus-Bar AB. 2 x 2206kW Niigata ZP-41CP controllable pitch Z-Peller azimuth thrusters, each shaft driven by a Nigata MD-8L28HX marine diesel engine rated at 2206kW provide the vessels main propulsion. The actuators data for the case study are shown in **Table 7**.

Table 7 Actuator's data table

Parameter	**Thruster 1,2,3**	**Thruster 4, 5**
Thruster type	Tunnel	Azimuth
Diameter, m	1.65	2.7
Maximum power consumption, kw	680	2206
x-position, m	33.9, 31.6, 29.2	-36.8
y-position, m	0	4.3, -4.3
z-position, m	1.45	1.8

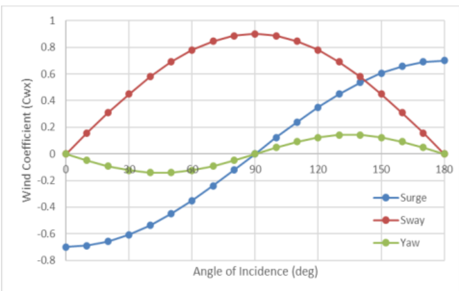
Results and Discussions

In this section, the results of dynamic positioning capability analysis are presented, and the analysis is performed by using the methodology on the case study of ROV supply ship which described before. The environmental forces acting on the vessel due to wind, current and wave are calculated first based on the profile and particulars of the ship. Then, the thruster calculation depending on the environmental forces are calculated to achieve the static balance. Also, Thruster optimization is done to evaluate the maximum weather conditions in which a DP vessel can maintain its position and heading for a proposed thruster configuration.

A. Environmental forces result

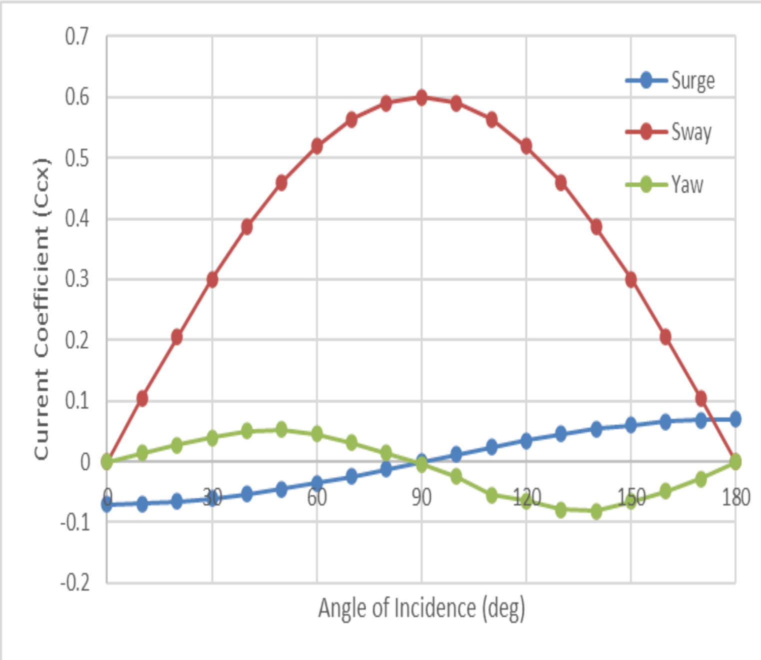
The environmental forces and moments are composed of wind, current and wave forces, and moments. For the support vessel with the above parameters sets, the obtained coefficients of wind loads calculated with DNV-GL method and the results are shown in **Figure 2**.

Figure 2 Variation of the wind load coefficients with incoming angles



Current load depends on the direction of attack angle and the main parameters of the hull. Only the basic features are therefore used to estimate the current load on the underwater hull. For a ROV Subsea support vessel, the obtained coefficients of current loads calculated according to DNV-GL method discussed in section 2.2.2, are shown in **Figure 3**.

Figure 3 Current surge coefficient at each angle of incidence



The calculation of the maximum capability determines the highest weather conditions in which a DP vessel can maintain its position and heading for a proposed thruster configuration by using the minimum expenditure of energy.

The thruster scenario estimation for the supply vessel mentioned in the previous section is put to test by setting the propulsion parameters as variables and the highest weather condition as the objective function.

The main variables of the optimization problem are the thrust output of individual thrusters and the working angle for the azimuth thrusters. The minimum and maximum values for the applied thrust and the operational angle ranges are given as boundary conditions. The constant current speed is equal 0.75 m/s and wave depending on the wind speed.

The main objective is to balance the incoming forces with the thruster-generated surge, sway and yaw, at the minimum expenditure of energy. At perfect balance, there will be no spare surge, sway and yaw moments left to alter the vessels position and heading. Mathematically, the sum of the forces acting in opposite directions will be zero. The procedure is adopted in the Excel based modified solver to determine the thruster configurations. Each of the surge, sway and yaw balance are set as the objective function of the problem.

For the supply vessel, the following input, thrust parameters and operational limits and optimization produce the wind speed equal to 31.99 m/s as the maximum attainable speed coming at an angle of 30 degrees with the corresponding wave height and crossing period. The final Environmental loads with its component's values are shown in **Table 8**.

Table 8 Environmental Forces at the maximum capability for 30 deg Heading angle

Environmental Constraints			
Incident angle of wind, current and wave (deg)	30		
Current Velocity (m/s)	0.75		
Maximum wind speed (m/s)	31.99		
Significant wave Height - Hs (m)	9.53		
Crossing wave period – Tz (s)	12.04		
Environmental Load	Surge-F x (kN)	SwayFy (kN)	YawMz (kN.m)
Wind Load	-149.61	256.3 3	6582. 65
Current Load	-1.96	43.28	929.5 3
Wave Load	-224.81	99.86	18.64
Total Environmental Force	-376.38	399.4 7	7530. 82

The optimized thruster configuration of the available thrusters to create a thrust to sustain the maximum weather condition which is presented above is shown in **Table 9** for the Heading angle 30°.

Table 9 Optimized Thruster configuration

Thruster	**Direction**	**Effective Thrust force (kN)**	**Power (kW)**	**Utilizat ion (%)**
Thruster 1	270	86.1	680	100
Thruster 2	270	86.1	680	100
Thruster 3	270	86.1	680	100
Thruster 4	359.1	28.1	164.8	7.5
Thruster 5	338	375.68	2206	100

B. DP Capability results

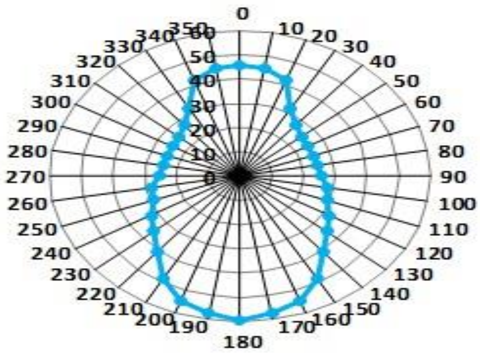
The main objective of the DP Capability Calculation is to obtain the DP capability Plot to find the maximum weather conditions in which a DP vessel can maintain its position and heading for a proposed thruster configuration. The maximum capability calculation done in the previous section for a particular wind, current and wave direction, defined current velocity, is repeated for 0~360 degrees range at 10 degrees increments. By allowing the environmental components to rotate in steps around the vessel, the results of a DP capability analysis can be presented by means of a limiting mean wind speed for a discrete number of wind angles of attack. The resulting polar plot is often referred to as a DP capability envelope.

The obtained values of maximum wind velocity that can be sustained by the propulsion system for each angle is saved along with the thruster configuration values.

The representation of the DP Plot follows IMCA-140 guidelines as discussed previously. The full DP plot at all heading angles from 0 to 360 is repeated at all the simulation cases.

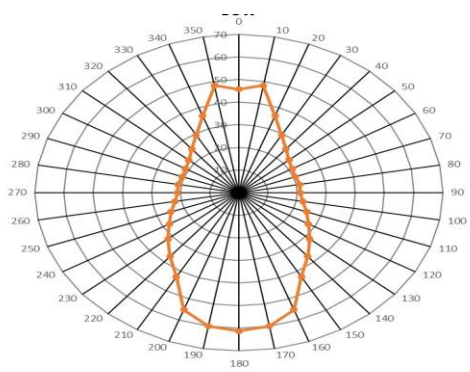
The simulation case study is organized by using the defined current velocity (0.75 m/s) and allowing the environmental components to rotate in a fixed step (10°) around the vessel. The first case study has all thrusters active and in operation which called the ERN condition. The DP Capability plot for the first case is shown in **Figure 4**. The scale 0, 10,…..,60 in the polar plot is defined as the maximum wind speed value in the specified wind direction 0-360 degrees.

Figure 4 DP capability envelop for the case study



The second simulation case study is organized by using the defined current velocity (0.75 m/s) and allowing the environmental components to rotate in a fixed step (10◦) around the vessel. The second case study have all thrusters from T2 to T5 active except thruster 1 (Bow thruster) which loss, so this case is called Loss of T1. The DP Capability plot for the second case is shown in Figure 5.

Figure 5 DP capability envelop for the case NO. 2



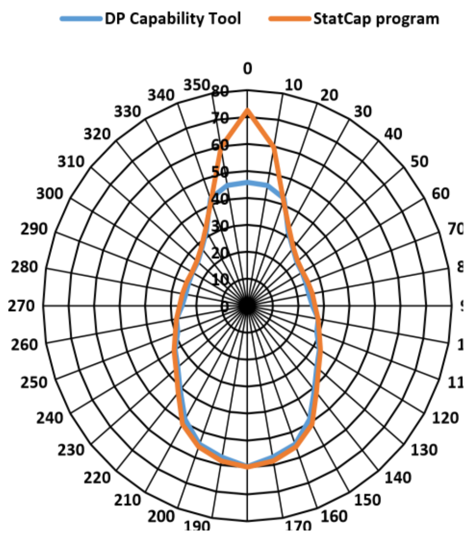
C. Validation study

In the validation part, the accuracy and reliability of the DP capability tool are tested. The DP capability plot considered as the backbone of the DP operations, is verified against standard commercial maritime computer program (StatCap program) which owned by The Kongsberg organisation.

The chosen supply vessel is already in operation with known DP characteristics. This ensures that the verification of the tool is not based on hypothetical methods, but on the authentic basis. The same procedures and methods that were used primitively for obtaining the DP plots for the vessels have been used in the optimization tool to visualize the difference between results and performances. It is important to note that only the obtained results are discussed hereafter and the detailed data of commercial interests are kept undisclosed.

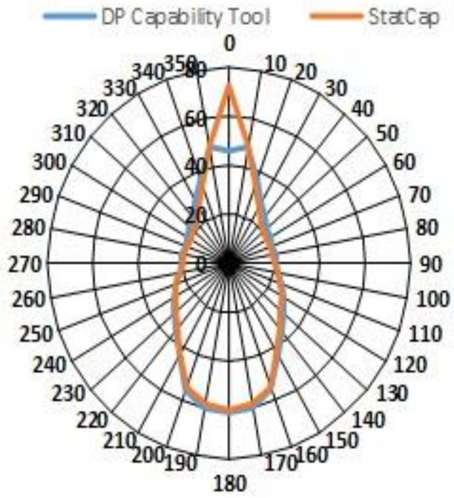
The DP estimation results for the supply vessel at case NO.1 is already presented in the previous sections. The graph on **Figure 6** is obtained when DP capability plot is compared with the available results from validation source of StatCap program at the same conditions. The vessel avails three bow thrusters and two azimuth thrusters and all thrusters are active for operation. The capacity and range of the thrusters are kept same.

Figure 6 Validation of DP capability plot results at case no. 1



The DP capability plot from the optimization tool is seen to closely resemble the reference DP plot from StatCap program. The difference between the two plots is located at the three angles of (350, 0, and 10) only but all other angles from 20 to 340 is closely the same results. The results of validation are shown a sensible accuracy. It is evident from the validation study that the DP capability tool can meet the criteria of capability analysis. The robustness of the tool comes from the usage flexibility over thruster configurations through suitable techniques and the ability to provide an automated representation of DP plots. The DP estimation results for the supply vessel at case NO.2 is already presented in the previous sections. The graph on **Figure 7** is obtained when DP capability plot is compared with the available results from validation source of StatCap program at the same conditions. The vessel avails two bow thrusters and two azimuth thrusters and these thrusters are active for operation and thruster no. 1 is loss. The capacity and range of the thrusters are kept same.

Figure 7 Validation of DP capability plot results at case no. 2



The DP capability plot from the optimization tool is seen to closely resemble the reference DP plot from StatCap program. The difference between the two plots is located at the Zero angle only but all other angles from 10 to 350 is closely the same results. The results of validation are shown a sensible accuracy. It is evident from the validation study that the DP capability tool can meet the criteria of capability analysis. The robustness of the tool comes from the usage flexibility over thruster configurations through suitable techniques and the ability to provide an automated representation of DP plots.

Conclusions

A study was carried out to estimate the environmental disturbances on an offshore vessel due to wind, current, and wave drift, hence, to predict the required counteracting thrusts and moments. Maximum wind speed at which the equilibrium between the effect of the environmental disturbances and the developed thrusts and moments is obtained.

The main outputs that work provides are the capability polar plots. These plots show the capability polar plot results at constant current speed of one knot and wind direction varying from 0 to 360 with respect to the x-axis.

For the offshore vessel, it is shown that for a wind direction of 30 º, the total environmental forces in surge, sway and yaw directions are -376.3 kN, 399.47 kN and 7530.82 kN.m, respectively and the maximum wind speed equals to 30 degrees. Those forces and moments are balanced with the developed thrusts and moments as shown in table 11 where thruster 1,2 and 3 develops 100% of its maximum allowable thrust with 270 degrees from the x-axis for offshore vessel.

The DP capability plot from the optimization tool is seen to closely match the reference DP plot from StatCap program. There was slight difference between the two plots is located at the three angles of (350, 0, and 10) only. The results of validation are shown a sensible accuracy. It is evident from the validation study that the DP capability tool can meet the criteria of capability analysis. The robustness of the tool comes from the usage flexibility over thruster configurations through suitable techniques and the ability to provide an automated representation of DP plots.

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