A Procedure for the Dynamic Positioning Estimation in Initial Ship-Design

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Rostock, February 2018

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TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

NOMENCLATURE

L_{BP}	Length between perpendiculars	[m]
L_{WL}	Loaded WL Length	[m]
B_{MLD}	Breadth moulded	[m]
T	Design Draft	[m]
C_B	Block coefficient	
Δ	Mass Displacement	[tonnes]
∇	Volume Displacement	[m^3]
ρ_a	Density of Air (1.226×10^{-3})	[t/m^3]
ρ_w	Density of Water (1.025)	[t/m^3]
g	Acceleration due to gravity (9.81)	[m/s^2]
P/(P)	Port side of ship	
S/(S)	Starboard side of ship	
COR	Distance of center of rotation amidships	[m]
DA	Dynamic Allowance	[%]
DAF	Dynamic allowance factor	
A_F	Frontal Projected area to Wind	[m^2]
A_L	Lateral Projected area to Wind	[m^2]
X_W	Longitudinal Center of Lateral Projected Area from AP	[m]
Z	Vertical Center of the Projected area from Waterline	[m]
C_h	Wind correction coefficient due to vertical centroid of area	
Cs	IMCA-140 suggested shape factors for exposed superstructures	
Vw	Velocity of Wind (one minute mean)	[m/s]
Vmax	Upper limit of wind velocity for calculation	[m/s]
Vmin	Minimum satisfied wind velocity	[m/s]
ϴw	Incident angle of wind clockwise from Bow	[deg]
Cwx	Surge Coefficient for vessel in wind	
Cwy	Sway Coefficient for vessel in wind	
Cwn	Yaw Coefficient about center of rotation for vessel in wind	
Fwx	Surge Load on vessel due to wind	[kN]
Fwy	Sway Load on vessel due to wind	[kN]

Mwn	Yaw Moment Load about center of rotation on vessel due to wind	[kN.m]
A_{CT}	Transverse Underwater Projected Area	[m^2]
A_{CL}	Longitudinal underwater Projected Area	[m^2]
Xc	Longitudinal Center for Lateral underwater Projected Area from AP	[m]
Vc	Velocity of Current	[m/s]
Ɵc	Incident angle of current clockwise from Bow	[deg]
Ccx	Surge Coefficient for vessel in current	
Ccy	Sway Coefficient for vessel in current	
Ccn	Yaw Coefficient about center of rotation for vessel in current	
Fcx	Surge Load on vessel due to current	[kN]
Fcy	Sway Load on vessel due to current	[kN]
Mcn	Yaw Moment about center of rotation on vessel due to current	[kN.m]
α	Incident angle of wave clockwise from Bow	[deg]
ω	Wave encountering frequency	[rad/s]
ω'	Non-dimensionalized frequency for scaling of wave coefficients	
Hs	Significant wave height	[m]
H	Average wave height	[m]
A	Wave amplitude	[m]
Cwvx	Surge Coefficient for vessel in wave	
Cwvy	Sway Coefficient for vessel in wave	
Cwvn	Yaw Coefficient about center of rotation for vessel in wave	
Fwvx	Surge Load on vessel due to wave	[kN]
Fwvy	Sway Load on vessel due to wave	[kN]
Mwvn	Yaw Moment Load about center of rotation on vessel due to wave	[kN.m]
Faddx	Additional surge Load on vessel due to vessel’s operation	[kN]
Faddy	Additional sway Load on vessel due to vessel’s operation	[kN]
Maddn	Additional operational Yaw Moment about center of rotation	[kN.m]
Tp	Peak period of wave	
Ts	Crossing period of wave	
Fx	Total Surge Load	[kN]
Fy	Total Sway Load	[kN]
Mz	Total Yaw Moment	[kN.m]

F_{WR}	Resultant Wind Drag Force	[kN]
F_{CR}	Resultant Hull Drag Force due to Current	[kN]
F_{WVR}	Resultant Load on vessel due to wave drifting forces	[kN.m]
Tp	Propeller Thrust	[kN]
Dp	Propeller Diameter	[m]
A_R	Rudder Area	[m^2]
λ_R	Rudder aspect ratio	
H_R	Rudder height	[m]
X_R	Longitudinal position of rudder from midship	[m]
Y_R	Transverse position of rudder from center line	[m]
δ	Rudder Deflection	[deg]
C_L	Rudder Lift coefficient	
C_D	Rudder Drag coefficient	
Ur	Induced water speed at rudder	[m/s]
F_{XR}	Drag at rudder	[kN]
F_{YR}	Lift force generated by rudder	[kN]
M_{ZR}	Moment generated at rudder	[kN.m]

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ABSTRACT

A Procedure for the Dynamic Positioning Estimation in Initial Ship-Design

By **Syed Marzan Ul Hasan**

The importance of Dynamic Positioning (DP) is growing because of the increase in the number of offshore construction sites requiring DP for their operations. Due to the high complexity of the calculation process, a few institutions are able to estimate the station-keeping capability of vessels. Since the DP capability of a vessel is directly connected to the hull form as well as the propulsion and manoeuvring system, it is obvious that DP is a major design task. Hence, it should be taken into account during the early ship design phase.

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 several DP vessels.

The studies of relevant parameters during the development of the DP tool gave rise to some valid topics requiring further analysis. These are also outlined as a measure for future considerations to increase the reliability of the methods as well as the estimation tool.

Keywords: Dynamic Positioning, DP plots, initial design, static capability, hull response, thruster control.

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1. INTRODUCTION

1.1 Use of Dynamic Positioning

Dynamic positioning (DP) is the ability of a vessel to maintain its position and heading. This is done by using the thrust from installed propulsion and manoeuvring system to counteract the environmental forces acting on the ship.

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. DP is used in the offshore industry for position keeping during the supply onboard operations or offshore underwater drilling. From the pipe-laying vessels to hydrodynamic research vessels, its job also includes the heavy-lift operations on jack-up vessels and the erection of wind turbines.

A further account on the usage of DP in modern vessels is represented in Fig. 1 on the following page.

1.2 Significance of DP

A safe, controlled and efficient handling of the vessel is indispensable for obtaining the desired service goals, often required in offshore conditions. Thus, DP capability is of high importance although DP itself is secondary to the complexity of the main operation. The system must be flexible, robust and include redundant capacities to handle gross failures so that the main objective is never compromised.

Additionally, a DP system has to be designed in such a way that, while maintaining the position and heading, it will also minimize the fuel consumptions and wear and tear on the propulsion equipment.

As the name suggests, the instant situational awareness and counteracting feedback mechanisms associated with DP system is a big field by itself. The present study deals only with the static balance required in the estimation of the characteristics during the design of a DP vessel.

Fig. 1: An account on the use of DP in various vessels

1.3 DP in Initial Ship Design

The initial ship design phase determines the initial cost as well as the lifetime operational realization for the whole ship. Therefore, the choice and the calculations of initial ship design parameters are of great importance. Depending on these set of values the most feasible concept is chosen for the project, the design is initiated, detailed production is carried out, and later, economic success is determined. All types of in-service and inter-related design considerations are made to optimize the ship to the owner's criteria and overall operational conditions.

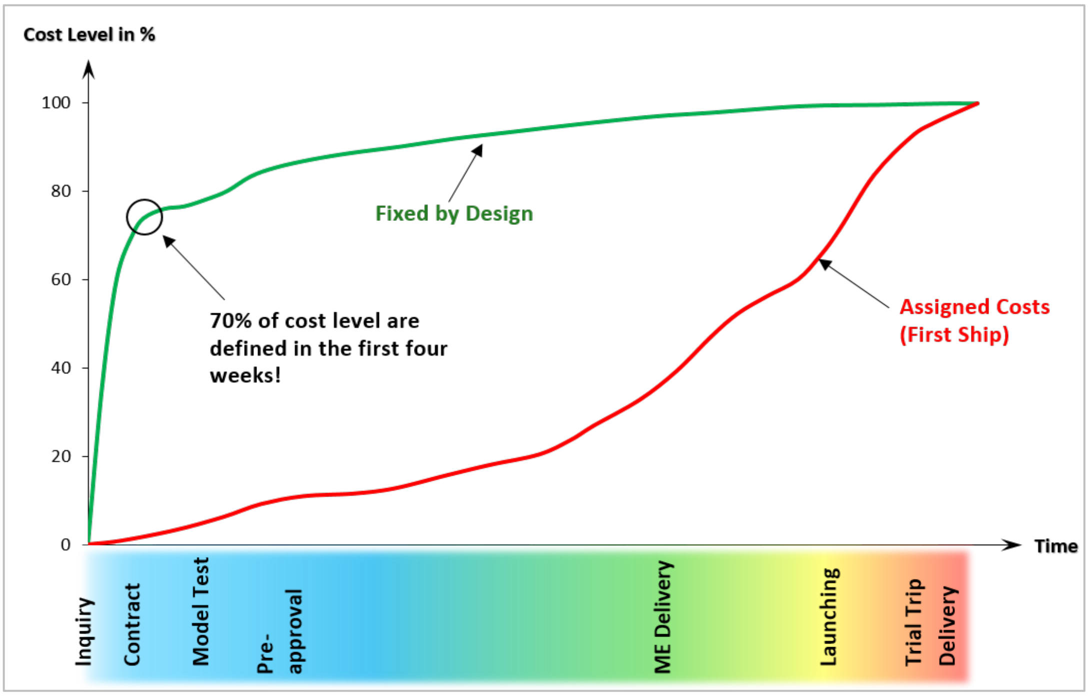

Fig. 2. Impact of Early Design Stage in determining the overall cost of the ship. [developed from source: (Krüger 2003)]

Almost 70% of the overall cost determinants are finalized in the initial design upon signing of the contract. A change in the later stages is very costly, in terms of both time and money. Therefore, a very fast, reliable and comprehensive set of design tools to automate the initial design phase must be present to be able to design a tailor-made vessel within a couple of weeks (Augener 2016). The tools include various design-parameter estimations depending on the type and operation of the vessels and other conditions, most of which evolve from ship and model research on similar ship series. In addition, others come from technical space requirements and relevant design experiences. The empirical formulae provide a quick way to propose and evaluate the particulars on their applicability for the vessel. However, the applicability of these techniques must be validated to ensure confidence in the adapted results.

1.4 Rationale for the present work

Calculation related to dynamic positioning requires a greater level of detailed data input to correctly and effectively predict ship performance. It is also necessary to know exactly the thrust forces required to counteract the ambient weather and operational conditions. However, at the primary ship design stage, estimation of final machinery capacity data is very difficult to confirm with accuracy. In most cases, the design conforms conservatively to the power requirements. This means that the final estimation for the DP requirements is inherently inexact and therefore predicting a ship’s performance is a great challenge.

A handful of commercial institutions are capable of estimating the DP parameters and usually relies on empirical results obtained from theoretical and experimental studies, and not from direct first-hand connections to the vessel’s own design and operational conditions. It is seen therefore that different companies employing separate methodologies and estimation techniques usually end-up finding different solutions for the DP capability of the same vessel.

In the design and analysis of DP, the involvement of third parties cause the projects to lose a certain level of confidentiality (Schutte 2016). Moreover, the shipyard or design house without knowing much of the details of the underlying procedures, have no way but to accept and rely on the results supplied to them.

On the other side of successfully predicting the design and operational characteristics of a vessel, is the failure associated with inadequate estimation or over-estimation of the requirements. For any vessel, which has to conform to its operational requirements, where the only way to prove her characteristics is through service trials, is a challenge. Any change will significantly delay the handover and involve further construction and demurrage costs. The situation is further aggravated if the changes involve propulsion.

The cost of change and rectification increases logarithmically with the passage of each stage from design to launching. The later from the design stage that the problem is identified, the larger is the reworking cost. Since for DP, thruster requirements are defined at the initial stage and the service verification is done through sea-trials, the scope of margin for errors is very little.

Therefore, it is necessary for a ship design office to successfully predict the DP capability, while ensuring a safe margin so that ship and the thruster designs remain valid for each other without differing greatly from the initial stage, to the later production and operational stages. This is the main challenge of the present work, i.e. to reliably integrate the DP capability calculation in the initial ship design stage.

1.5 Final Goals or Objectives of the technical work

The present paper describes the details of creating a tool with DP optimization capability. The main objective is a simple to use and for first design steps, a reliable enough tool for Dynamic Positioning capability estimations. The success of the final technical work depends on the realization of the following:

(i). The general concept of the calculation/solver module.

(ii). Plug in modules for different external forces (wind/current/wave).

(iii). Plug in modules for different thruster/propulsor devices.

(iv). Plugins for special constraints as e.g. Maximum available power.

(v). Result plots and lists (standard DP plots).

(vi). Additional results for power demands - peaks and averages.

(vii). Verification with results for different ship types already built.

The programming for the optimization is done in an Excel environment for the easy input and the presentation of results.

1.6 Organization of the Thesis

Having discussed the basic features and requirements of DP in the operation of a vessel, and the necessity of a DP tool to facilitate the capability estimation in the initial design phase, the present paper elaborates the processes undergone during the course of reaching the final objectives of the related technical works done during the internship.

In the chapters to follow, a review of previous works is discussed and evaluated for obtaining vital insights of the optimization process. The associated variables and functional criteria for parametric tooling are analyzed for determining the requirements. Based on the background study, a working methodology is formulated where the scopes and limitations are defined. The procedure towards static balance and various modes of estimation and presentation of results are ventured. The developed approach is realized through discussion of various methods that can be used in the estimation of the external load components of wind, current, wave and additional forces, in terms of surge, sway and yaw. The thrust from various actuators and their optimization is described in the chapter related to thrusters.

The stages towards final DP plot through step-by-step optimization process is reviewed through actual design walkthrough in the DP capability estimation chapter. The process of obtaining output and visualization of results are also described.The validation of the excel optimization process is done with standard optimization software to test the accuracy. Further verification of results is done in terms of generated DP plots with the vessels already in operation.

The study concludes with the identification of related advantages and shortcomings giving reference to future works that will increase the depth and accuracy of the developed tool.

In a nutshell, the present paper describes the background study, formulation and development of the working methodology as well as the functioning tool, testing its reliability, and finally mentioning options for future improvements.

2. BACKGROUND STUDY

2.1 Literature Review

A wide variety of research works and existing guidelines are available on the design and operations of the DP systems. Since the study relates to the development of a functional tool, a detailed documented approach was tried rather than just summarizing the findings. The following paragraphs describe the related review of the literature, in the order of their importance within the calculation process.

2.2 Standards and Guidelines

International Marine Contractors Association (IMCA) set out a number of guidelines regarding the design and operation of the DP vessels. Among their series of publications, (IMCA-140 2000) is considered as the current industry standard for the calculation, representation and comparison of results from DP capability analysis. Other of their published guidelines like IMCA-103, 166, 178, 182 etc. (IMCA 2007), mainly deal with the safe operational attributes and consideration of Failure Mode Effect Analysis (FMEA) of different kinds of DP vessels.

The guidelines on the dynamic positioning design philosophy in (DNV-GL 2015) is believed to be the one of the complete reference points for the purpose of the classification of DP Vessels. It acts as a guidance document to aid in the design of DP vessels for the industry and also introduces the associated classification rules that should be complied with if a ship with DP has to be registered under DNV-GL DP Notation. Other related extensive classification and construction guidelines are also available from the ABS Guide for Dynamic Positioning Systems (ABS 2014).

The equipment class for Dynamic positioning is followed according to the guidelines set by the IMO Marine Safety Committee Circular-645 (MSC 645 1994):

- Class 1 – no redundancy.
- Class 2 – redundancy of all active components.
- Class 3 – redundancy and physical separation of all components.

2.3 Environmental Constraints

The external data required for the estimation of vessel thruster characteristics are the wind, current and second order wave drift loads. The wind and current data can be obtained from the predictions based on existing database combined with empirical formulations, or alternatively from wind tunnel tests on the DP vessels (NA-RINA 2009). Safe operation limits are to be defined for each operational task-based geographical location that the vessel will be deployed.

IMCA (IMCA-140 2000) guidelines consider the maximum permissible environmental forces assigned to wind speeds over incident angles of 0 to 360 degrees around the vessel. Higher wind leads to higher waves drift forces while the current is assumed to be constant. It is also assumed that all environmental forces are collinear to neglect their interaction effects and apply a conservative approach corresponding to the maximum possible ambient condition. In all cases, fluctuating loads are replaced by their mean effect on the vessel.

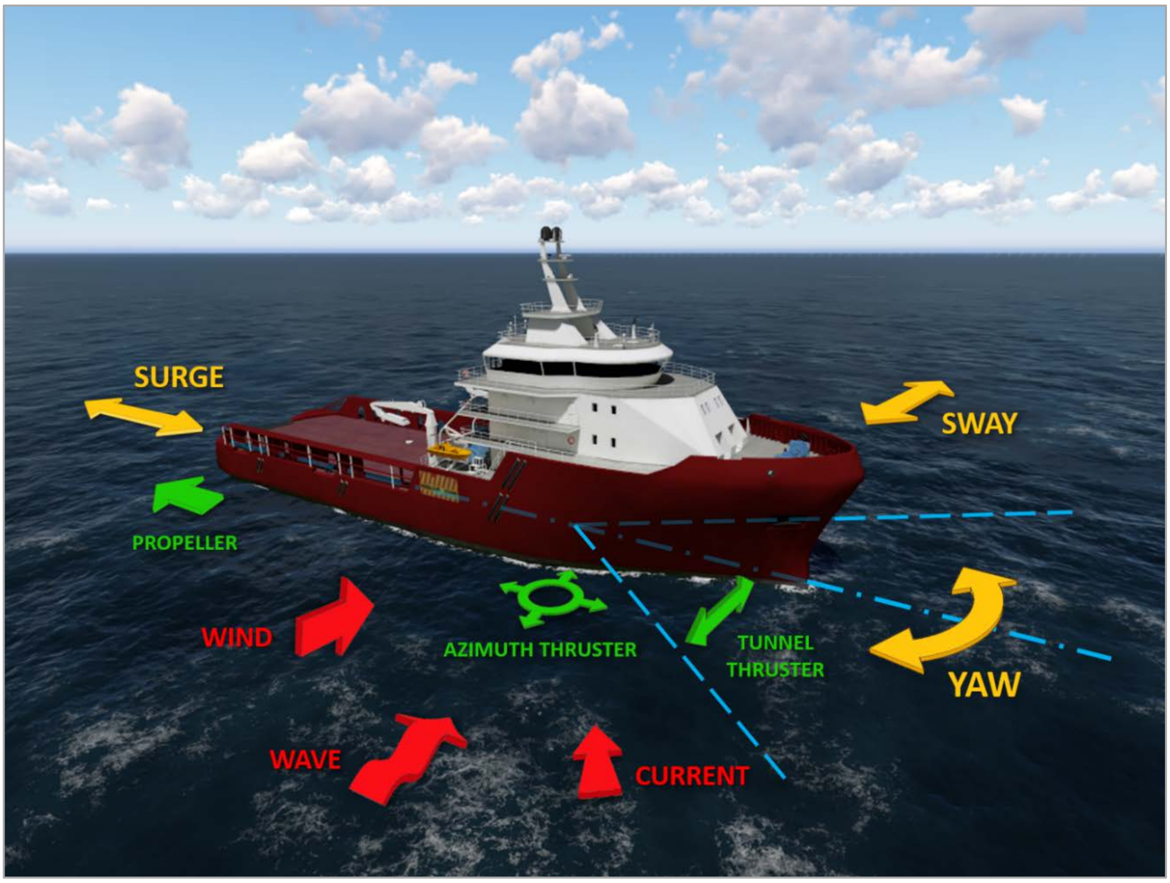

Fig. 3: External forces and thruster balance requirement for station-keeping ability

Lubcke *et al* (2015) consider the importance of taking into consideration the Dynamic Positioning aspects in the early ship design stages. In the paper, they have developed a new method to predict the limiting environmental conditions. The forces and moments (static effects) are equilibrated with the propulsors' thrust using optimization algorithm.

2.3.1 Wind Loads

Like all environmental phenomena, the wind has a stochastic nature, which greatly depends on the time and location (Journée 2000). The study shows a considerable amount of fluctuations in velocity and direction. It is standard to calculate the wind force acting on the vessel corresponding to the wind speed at 10m above sea level.

Additionally, the increase in wind intensity with the increase in height must also be taken into account. The hourly mean is replaced by a one-minute mean to take the speed variation into account (IMCA-140 2000). Maximum prevailing wind conditions can be taken from Beaufort wind reference scales considering a safe operation of the DP vessels itself.

Loads are different for ships that operate at different drafts. In case of a tanker, for example, the difference between the projected area to wind at loaded and ballast drafts, is usually large. However, this is disregarded in the present study and all vessels in DP are considered to be operating at their loaded draft.

Another important consideration that is excluded from present analysis is the change in the surge, sway and yaw coefficients with the change in the position of the superstructure whose effects are seen from the study of R. Owens and P. Palo (1982).

Wind loads can be predicted by various means, most popular among them is the coefficients obtained from the work of W. Blendermann (1996). Other methods that can be implemented are the experimental and empirical results obtained from IMCA recommended method obtained from the study of U. Nienhuis (1987).

Alternatively, from Isherwood (1972), G. Hughes (1930), or simply using the method of Fujiwara *et al.* (2012).

The projected profile variation in the area for the wind loads is also not linear, as can be seen from the example figure below (SIGTTO 2007). IMCA-140 directs the taking into account of such shielding effects.

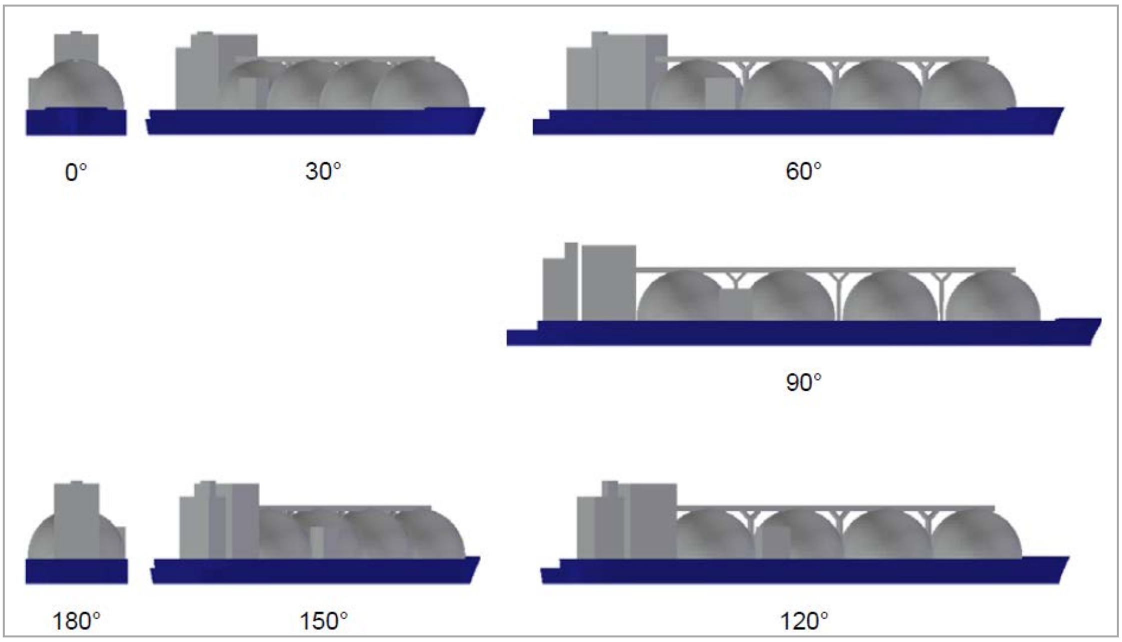

Fig. 4. Non-linear variation of projected wind area for LNG Carrier (SIGTTO 2007).

2.3.2 Current Loads

The surge, sway and yaw loads due current drag are calculated by simple formulas and relevant drag coefficients (B. V. Ubisch 2004). More reliable data can be obtained from the model testing values. The current load is seen to vary across different angles. It is better, therefore, to work with the maximum induced loads whichever it may be, at some different angle, but then using it on the same incident angle as the wind or the wave drift forces.

Coefficients from the work of U. Nienhuis (1987) can be used as a first approximation of the current loads on the ships. Experimental regression data are available for five different ship types: Supply, Ferry, Container, Tanker, and Drillship. OCIMF (1994) data can also be valuable in the estimation of the current load on the large ship hulls.

Moreover, external results from the calculation employing Strip Theory can also be used in the current load estimation. The current load can be alternatively estimated as a still water resistance without generation of waves corresponding to a fixed towing speed at different directions of travel. IMCA recommends a constant current speed of 1 knots and DNV-GL has fixed current speed according to the wind direction. These correlation data are shown in the tables given in Appendix-A6 & A8.

2.3.3 Wave drift forces

Unlike wind and current, wave forces are transient which includes an oscillating motion due to the harmonic first order linear wave loads, the low-frequency structural response (Journée 2000), and the mean displacement or wave drift due to the second order non-linear wave potential effects. Only the third type is of concern to the design of DP capability. The other two are oscillatory with a mean about zero and although they affect the amplitude of motion for the vessel, counteracting them would be unwise leading to excessive fuel consumption and wear of propulsive machinery (Augener 2016).

The wave drift forces are mainly derived from model testing or real coefficient data obtained from sister ships or similar vessels. The wave height is considered a linear function of the wind speed. If the swell is also considered, it is independent of the local wind speed. It is important to note that the wave drift forces are very much period dependent as short-steep waves give higher forces than long-waves with the same wave height.

R. van't Veer and M. Gachet (2011) discusses a methodology on how a capability assessment can be made in the early design stage of a vessel. They pointed out vital insights in the consideration of heading, position and the variable effect of the environmental forces over time.

Numerical results are also useful in determining the low-frequency drift forces. However, a correction to the calculation of DP capability may be required to account for the time variable wind and wave drift forces.

Nienhuis (1987) suggests that wave forces can be calculated by scaling of drift force transfer functions obtained for other ships. IMCA-140 adds to it that it can be done provided that the scaling is done from a reasonably similar hull or column shape. The 2nd order wave drift theory as defined by J. A. Pinkster (1980) and Faltinsen *et al* (1978) based on the expansion series of the wave forces using potential theory, shows that the second order wave drift forces consist of 5 contributions:

(i). Waterline integral of relative wave elevation

(ii). Dynamic (Bernoulli) pressure integral

(iii). Moving body in oscillating pressure field

(iv). Rotation of the inertia forces

(v). Pressure integration of 2nd order wave potential

B. V. Ubisch (2004) mentions that wave drift forces can best be obtained from model tests. When calculating the wave drift forces, the wave height is seen as a linear function of the wind speed. A swell component may also be present when the significant wave height is being considered. Therefore, the wave spectrum and the selected wave period in relation to the wave height are very important in calculating the total wave drift force.

2.4 Operational Factors

Along with the ambient weather factors, a vessel may require DP to suit its operational requirements like pipe-laying or offshore cargo transfer. In such cases, the extra loads must be taken into account while estimating the thrust power allocations.

These extra load, however, may also be time-varying or instantaneous. For DP estimation, the probable additional forces are to be taken as a mean continuous operational load. This approximation must also be sensible such that the occasional fluctuations can be handled with the reserve power of dynamic allowance.

2.5 Dynamic Capability and allowance

DP Capability analysis is inherently quasi-static meaning that the mean environmental forces are balanced by mean thruster forces. However, dynamic nature of the real world problem requires transient condition analysis including failure and recovery (Smogeli 2013). Lubcke *et al* (2015) used the results from static DP estimations to calculate the dynamic effects due to wind and waves in the time domain. The wind forces prediction uses the same method taking into account the speed, direction and the projected lateral area. The fluctuation of the wind speed and direction is modelled by using a spectrum. A similar process is done for the current forces but the speed is assumed to be constant. The usual diffraction-radiation sea keeping method is used to calculate the time-varying wave drift forces.

Since the shipbuilding contracts of these vessels specifically mention the maximum allowable positional and heading limits, the dynamic DP analysis in time-domain is also a very important consideration in the initial design stage. Operability analysis and fuel consumption are directly related to the dynamic ability of the vessel. This requires capable algorithms with positive feedback and filtering techniques for real time-variant load effects and their corrections through thrusters.

The present work, however, will concentrate on static DP analysis keeping a safe power margin for dynamic allowance. The method of allowance for the ‘spare’ thrust is to be mentioned in the capability envelope sheet and can be calculated from the spectral densities of wind and wave drift loads. Typically, 15-20% of the thrust is additionally reserved for handling the dynamic loads. IMCA (2000) mentions dynamic allowance for varying load at operational conditions to be taken between 15-17% higher than the time average. Lloyd Register’s PCR consider a restoring force of 20% meaning that 80% of the thruster’s nominal force will be taken into account during the calculation of DP capability (Herdzik 2013). DNV-GL recommends the use of 25% extra thrust on the calculated configuration to consider the dynamic nature of the seaway.

2.6 Propulsion Arrangement and Constraints

The dynamically positioned vessel has to be able to provide the desired thrusts execute manoeuvres in the surge, sway and yaw from zero to full magnitude and in all directions as required by the DP. Moreover, these might have to be done for extended periods at an optimum speed of the vessel over extensive distances.

There are different actuator types like the azimuth thrusters, fixed direction propulsors, and hybrid concepts that utilizes a combination of azimuth thrusters and fixed-direction thrusters. The drive system can be composed of electric motors, hydraulic motors, and direct diesel engine drives. It is considered that the DP system is only as effective as the efficiency of its lowest-performing thrust link. While there are advantage and disadvantage for each of them, their suitability must be carefully thought in terms of operational factors and economic criteria before assigning them to a vessel.

Secondary effects due to lift forces generated by rudders over different angles of attack at 35 degrees port to 35 degrees starboard must be estimated. However, only the rudder behind forward thrusting propeller is considered active due to its presence in the increased relative flow, and the rudder behind reversing propeller is disregarded.

The minimum number of thrusters depend on the forces developed in the surge, sway and yaw. The classification society's redundancy requirements consider the worst-case failure scenario, but even in this case, the DP capability must meet a minimum defined capacity.

2.7 Interaction Mechanism

The thruster efficiency is considered to be one the most difficult variables to determine since there are many influencing factors. Model tests are done, but by far, the best method to estimate the interaction effects is to make full-scale trials.

It is of great importance to note that the cumulative effort with all thrusters working together is less than the sum of individual thrusters operation measured during segregated trials (B. V. Ubisch 2004). This shows that the thrusters also interfere with each other operations when working together.

Standard model experiments conducted at the MARIN (Ir. Quadvlieg 1998) mentions the importance of considering the water depth and sidewall effects to the propulsive forces from the thrusters. Interaction mechanisms can be grossly stated in terms of:

(i). Bow Thruster- Hull interactions

(ii). Bow Thruster-Current interaction

(iii). Thruster to thruster interactions

(iv). Turning direction of propellers: blockage of flow and Hoovegard effects

(v). Quay and nearby vessel interactions

It is difficult to correctly quantify the interaction effects while it is easier to implement a calculating scheme considering the propellers, rudders and thrusters neglecting the interactions and then adding an educated margin to allow for the interaction effects. Neglecting, however, may result in erroneous conclusions.

It is evident that (IMCA-140 2000) specifications related to the interaction problem are very basic coming from the general rules-of-thumb. It also includes the simplicity of calculations, the coefficients derived from experiments of other vessels. It is deemed necessary to compare trustworthiness of calculations against a realistic picture of the operational vessel. This is because the difference between the theoretical and actual capability can be significant as pointed out by D. Phillips *et al.* (2006) where they emphasized on the accurate modelling of the interaction effects.

Forbidden zones are to be imposed to avoid thruster interactions between themselves. This is generally done by restriction to the thrust angles and also by positioning the thrusters in suitable locations where the interaction effects will be minimum. Further details on the interaction can be obtained from the works of E. Lehn (1985) & (1990) and Svensen (1992).

Thrust loss in the transverse thrusters can happen due to the axial and transverse current, waves and Coanda effects. Thruster-hull interaction includes hull friction, pontoon blockage. An improvement in the problem can be seen when the thrusters are tilted to some degrees about their vertical axis near the hull. Depth under the water body has also its effects in the current and wave loads as can be seen from the figure below. In the present study, the vessels are considered to be operating in DP at infinite water depths.

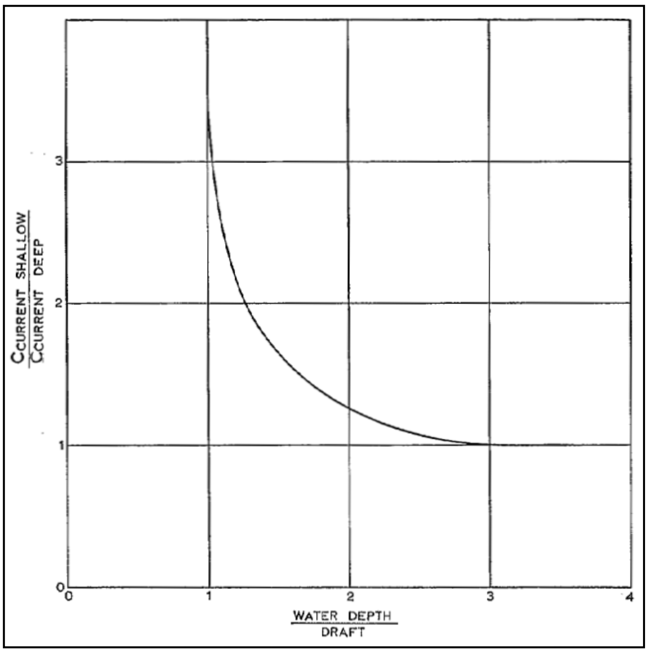

Fig. 5. Effect of depth of water below hull to current coefficients.
[source: Oortmerssen (1973)]

However, if it is decided in the beginning to neglect the interaction effects, all the thrusters are considered to be producing their nominal thrust regardless of the operating conditions.

2.8 Optimization Problem

The approach towards the need of DP, effective power requirements and positions may have several independent solutions but a common optimized solution satisfying all the requirements must be found. (NA-RINA 2009).

A simplified DP solver for a vessel with two azimuth thrusters and one bow thruster have no less than 5 unknown themselves: the three thrusts and the two steering angles. When multiple steerable thrusters, tunnel thrusters, propeller and rudders are considered, coupled with the operating conditions, limitations, and interactions, a great deal of calculation volume, as well as complexity, must be dealt with to satisfy the objective value. Solving thus takes in the form of optimization problem utilizing advanced optimization techniques rather than a simple convergence study through linear iterative solutions.

For a single angle of incidence of wind, wave drift and current, optimum values must be found using the available thruster combination, position and arrangements, their respective steer angles, including propeller pitch, rpm, as well as rudder manoeuvring angles, so that the external loads can balance out. The goal or objective function, in this case, can be a highest ambient load that can be handled or nullified using the lowest thrust.

It is interesting to note that it is better to incorporate a convergence allowance rather than equating to an exact force and moment balance. This allows a better convergence rate and wider variable consideration possibilities. An allowance of 1kN of force and 1 kN.m of the moment can be justified by the fact that the 25% margin for dynamic allowance is far larger (in the order of 500~1000 kN) and can compensate an result error of such smaller proportions.

The paper by Mingyu Fu (2010) presents an optimization method based on Genetic Algorithm to calculate the controlling capability of the dynamic positioning system. This mainly deals with the study for reducing the calculation time for the dynamic response. It is mentioned that traditionally, the design method for the thrust system of a DP vessel can be divided into two parts: by calculating the extreme data from measurements or model experiments and then distributing the thrust force to counteract the ambient forces.

2.9 Effect of Type of Vessels

The variation of vessels' underwater and superstructure profile results in non-linear variation of force coefficients. Variation of the type of vessels adds further complexity to the problem since most of the coefficients are obtained from generalized experimental studies. It is thus difficult to exactly find the relevant coefficient for the calculating vessel.

Moreover, if the vessel is of unconventional form or characteristics, the estimation difficulty increases further. It is therefore very logical to have inherent faults in the estimation process. So, a variety of methods must be tried to test for the accuracy of the obtained results. The below shows as an example, the variation of current load coefficients for a different angle of attacks for 5 types of vessels with conventional hull forms.

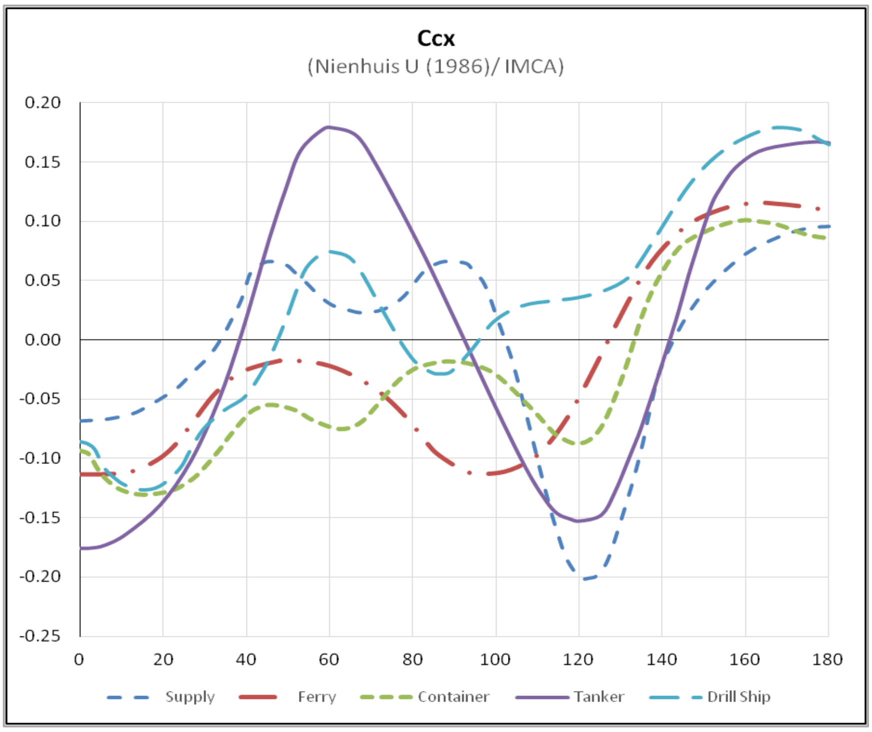

Fig. 6. Variation of longitudinal (surge) current coefficients for different vessel types. Digitized by the author from (Nienhuis 1987) for integration into the optimization process.

2.10 Full thrust and worst case failure considerations

The Failure Mode Effect Analysis (FMEA) can be dealt after the basic-operators and key-data have been assembled. It allows for any DP operator to evaluate the capability in the event of any major failures. (NA-RINA 2009).

Smogeli *et al* (2013) mention that the consideration of full thrust and worst single failure mode determines the stakes regarding cost and safety and allows planning for weather operational window for the position and heading excursion limitations as mentioned in the construction and charter agreements.

IMCA (2007) recommends that the maximum continuous operational station keeping ability should be calculated for:

(i). All the thrusters with maximum thrusts.

(ii). All thruster except the most effective thruster operational with highest thrusts, i.e. maximum operational possibilities for the rest of the thrusters after worst single failure with a loading not exceeding the available handling power.

Besides this, the plots are represented within the single DP plot and must be verified in the first year of the DP operations. It is mentioned (Holvik 1998) that the DP system is only as good as the weakest point in the chain meaning that the control system combining thruster, generators, motors, sensors and reference systems have to be based on a certain standard and accuracy in order to ensure the required operability and safety.

It is suggested by Herdzik (2013) that the dynamic failure criteria, namely, the drive-off, drift-off and force-off must be considered and thought of during the early design stages in terms of DP capability and the functioning system as a whole.

2.12 Traditional DP Scaling (ERN/PCR)

It is important to know that traditionally DP vessels were assigned with ERN or PCR numbers as a representation of their capability. Ubisch *et al* (2004) mention the application of classic Environment Regulatory Number (ERN) developed by DNV in the 70’s. Although the thruster, restoring forces and hull efficiencies were not considered, the number usually portrayed and widely accepted to represent the capability of a vessel in dynamic positioning. ERN method focuses on simplicity but greater accuracy than the methods prevailing at that time.

LR has been mentioned to take a completely different approach to determining the capability of the vessel based on the Performance Capability Rating (PCR). Developed in the 80’s, the wind and wave data are taken from the fully developed North Sea Spectrum. The thruster efficiency is also taken into account. The current speed is considered to be 1m/s and a Restoring force of 20% of the total forces. This makes the available thrust less than 80%. The first of the two digit group represented the time the vessel can keep position providing all systems are working and the second group indicates the time the vessel can keep the position in the event of failure of the most effective thruster.

In recent times, DNV-GL proposed a new rating system of DCN 1~11 (DP capability number) based on the Beaufort wind scale.

The present study will, however, be limited to the standard application of (IMCA-140 2000) guidelines followed from the IMO MSC-640. The positioning ability of a DP vessel is represented typically as a set of polar plots analytical presentation of the vessel’s performance during station keeping operations while exposed to external forces. It is mentioned that a dynamic time-domain analysis is not required by the classification societies (DNV-GL 2015) referring to the ship’s initial design stage.

3. METHODOLOGY AND CONCEPT DEVELOPMENT

This chapter deals with the formation of the optimization algorithm. Based on the background study, the input, processing and output scenarios are defined. A calculation methodology is defined by a flow-chart and the calculation processes, techniques and their limitations are discussed afterwards.

The external forces are sourced from their respective coefficients depending on the vessel's particulars. The thruster configuration parameters are defined to be used along with their position and power constraints. The variables defined in the initial design stage are used in steps and loops for the calculation of loads for all external forces in terms of surge, sway and yaw. Static capability considers the balance of forces and thrusts for one incident speed and direction. Thrust capability is derived from the optimization of variable thrust configurations. The DP capability deals with overall progressive optimization at variable wind speeds and directions.

Before describing further, it is first necessary to discuss the significance of static balance in the calculation of DP capability.

3.1 Static Force Balance

The first step in the design process is to establish the desired capability for the vessel as mentioned by the owner. This leads to the estimation of the amount of power required for the optimum operation of the vessel. Other factors that are also needed are the description of the industrial mission of the vessel, the operational uptime, post failure thrust capability, environmental parameters under which the vessel will operate, desired transit capacity, and finally, the limitations due to the interactions. The propulsion system must have the capability to generate thrust in full 360 degrees of the vessel. The static analysis gives the equilibrium of the steady-state forces and moments of the vessel and establishes the static holding capabilities. However, at the preliminary stage, the calculation is just an estimation and not a full evaluation, the latter being established only through future full calculations and after the sea trials and at actual operations.

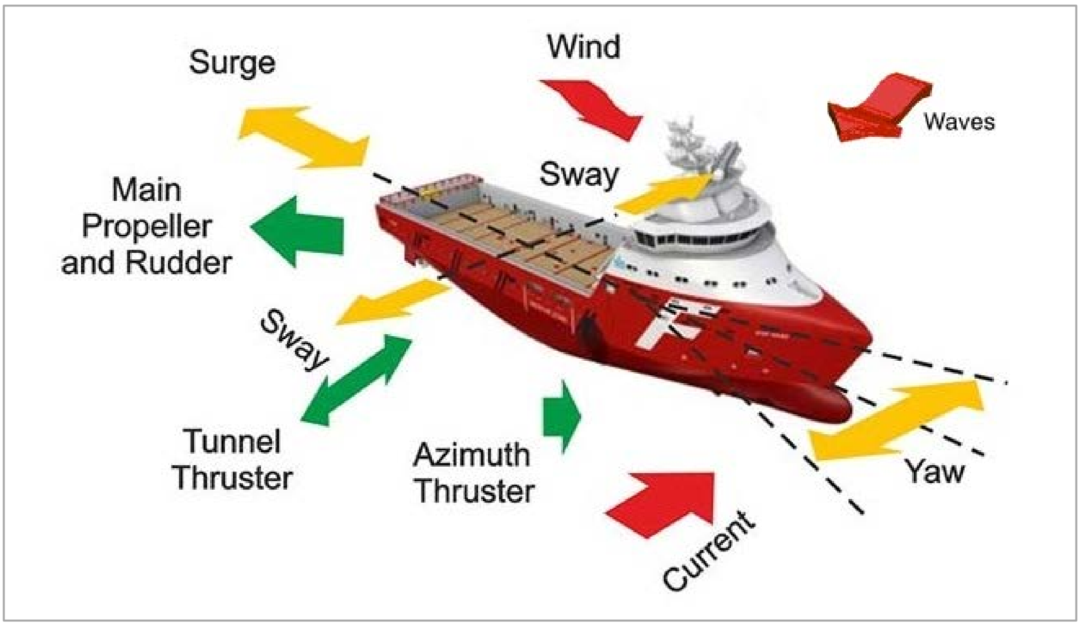

Fig. 7. Incident forces and thruster balance for a vessel with DP capability [source: (DP Marine 2017)]

One vital assumption in the static DP capability analysis is that the vessel is considered to be fixed at one position and heading as its thrusters work in balancing the ambient load on the vessel. Although static balance is not an exact representation of the vessels DP capability in the actual sea, the DP plots that can be generated from them are recognized in the industry (Schutte 2016).

IMCA standards (IMCA-140 2000) can be used as the first-hand reference for the development of any tool assessing the DP capability. Since only the surge, sway, and yaw motions are considered to be typically constrained by DP, only related drag coefficients are important to employ empirical formula and load relations to calculate the effective directional forces. Most of the coefficients come from detailed model tests in towing tank or wind tunnel.

Another close real-world application of the static DP capability calculation is the crabbing capability of the vessel. Quadvlieg *et al.* (1998) mention that it may be possible to save a lot of time, fuel and money related to the berthing and un-berthing of the ship throughout its operating life. Crabbing considers the transverse motion of the ship at negligible or zero forward speed. The static balance of DP vessel is very similar in terms of force and thrust balance considerations. Crabbing involves the main propellers, rudders, the stern and the bow thrusters. At the preliminary design stage, it may be useful in terms of time to calculate using force balance rather than considering the power of machinery involved. However, empirical relations can always come handy to predict the amount of thrust that can be generated over a given power range.

The force balance ensures positional stability while on the other hand a moment balance ensures heading stability. The empirical equations take the form (Fig. 8 represents general concept on the sign conventions used in the force balance) :

In longitudinal direction (Surge – ‘x’ direction):

$$F_{x-WIND} + F_{x-CURRENT} + F_{x-WAVE} = F_{x-AZI.} + F_{PROP} + F_{RUD.\ DRAG} \quad (1)$$

In transverse direction (Sway – ‘y’ direction):

$$F_{y-WIND} + F_{y-CURRENT} + F_{y-WAVE} = F_{y-BOW\ TH.} + F_{y-STERN\ TH.} + F_{y-AZI.} + F_{RUD.\ LIFT} \quad (2)$$

Considering Moment (Yaw – ‘Mz’ about midship/center of rotation):

$$M_{WIND} + M_{CURRENT} + M_{WAVE} = M_{BOW\ TH.} + M_{STERN\ TH.} + M_{AZI.} + M_{PROP.} + M_{RUDDER} \quad (3)$$

3.2 Sign Convention

The sign convention is adopted from the IMCA-140 guidelines plus some additional considerations for easier calculations and referencing.

Sign Convention:	**(+ve directions)**
1. Position	Forward of Midship
	Starboard OCL
2. Force	Forward direction (Stern to Bow)
	Center outwards Starboard
3. Moment	Clockwise about Midship
4. Rudder/Azimuth Angles	Clockwise from 0 degrees

As shown in the above table distance and force is considered positive in direction forward of amidships and the moment, rudder and azimuth thruster angles are considered positive clockwise. This means that all the environmental loads coming from 0 degrees (bow) to 90 degrees (beam) from starboard clockwise are negative being inwards. The environmental forces become positive when considering 90~180 degrees, while the transverse ambient forces remain negative. This is better visualized in the given figure:

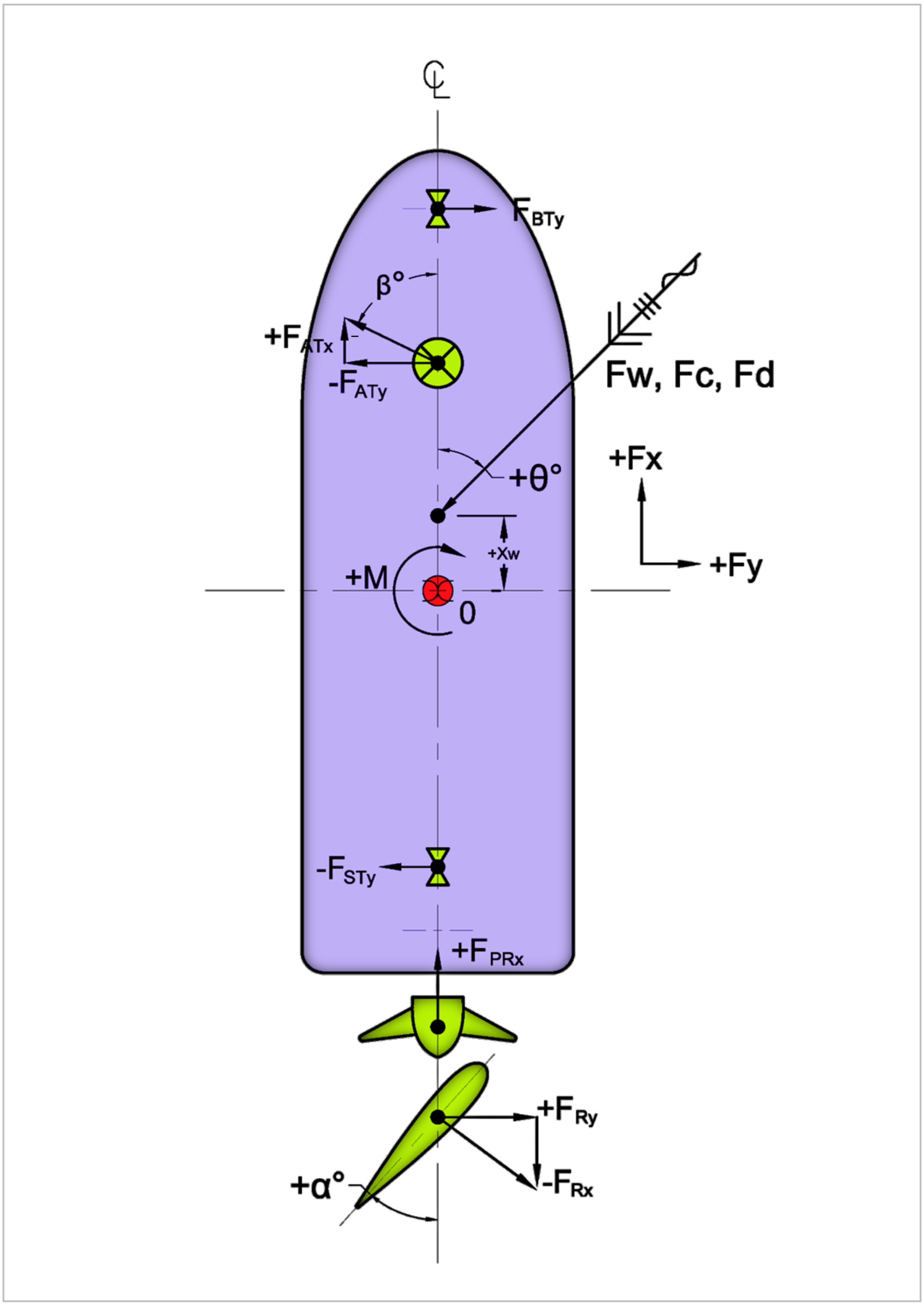

Fig. 8. An account of Force considerations and conventions used in calculation process.

3.3 Formulation of the Optimization Module

The DP capability calculation is done in four phases. This involves the estimation of the external forces acting on the vessel, optimization of thruster configuration for a static balance, checking if higher forces related to the higher wind speeds can be sustained at the particular incident angle. Then, the process is continued for the next angle, and in this fixed increment steps, up to 360 degrees. The final result is represented by interpolating the maximum sustainable wind speeds in a polar plot.

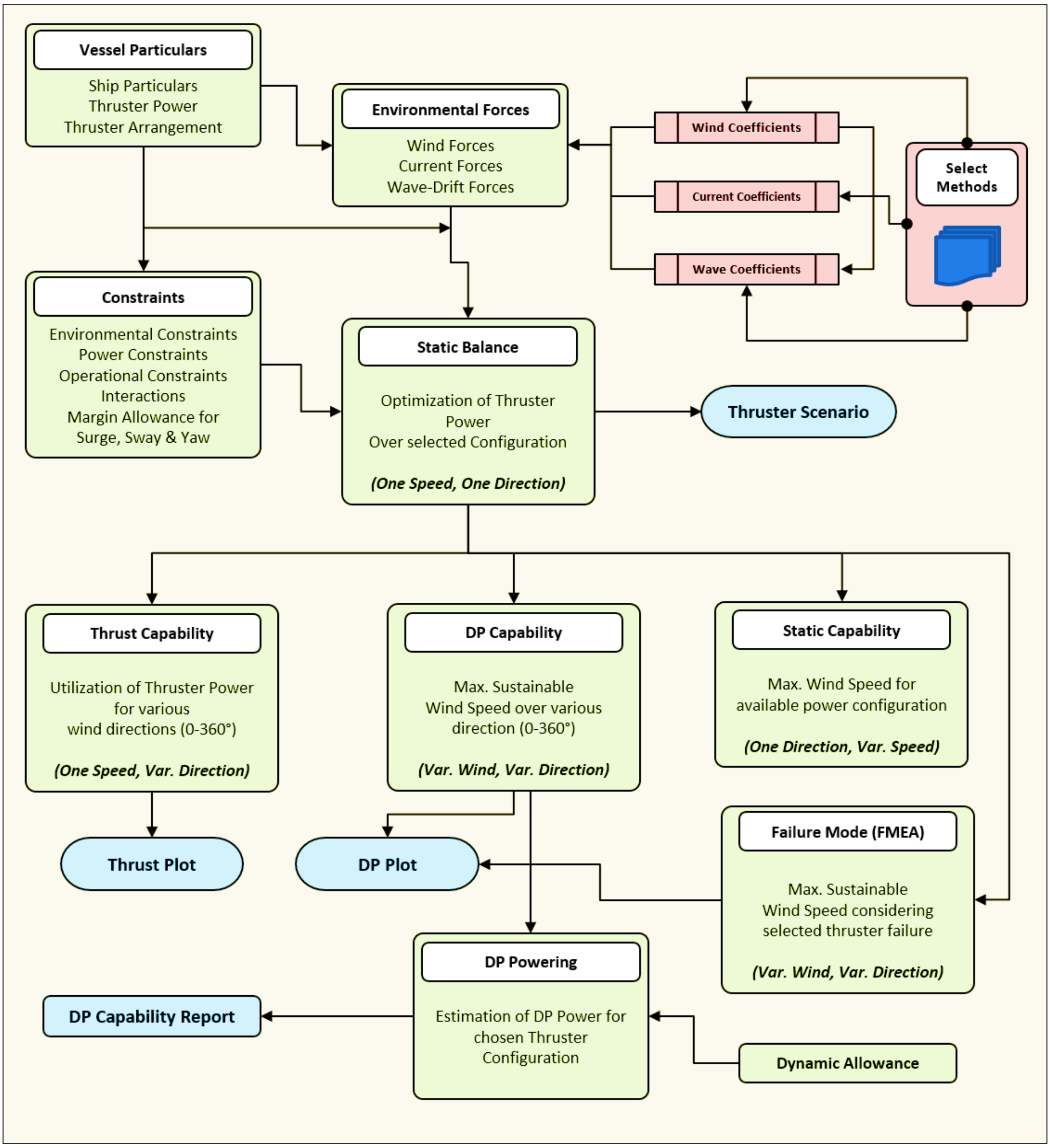

Fig. 9. Structure of the DP capability estimation process.

The work flowchart in the previous page represents basic working process selected for the DP tool. 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.

The flowchart starts with the input of the basic hull parameters, thruster power and positional data, projected lateral and frontal areas etc. The parameters related to the calculation of the environmental load and power are constrained in terms of operational and interaction limits. The margin for the dynamic allowance is also defined in the constraints section. The environmental force calculation combines the basic hull data and the wind, current and wave coefficients to calculate the total surge, sway and yaw load 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 data-sets are used to calculate the static balance. The thruster output is varied within the range such that the surge, sway and yaw moment they generate balances the incoming external loads. The output from this calculation is represented in the thruster scenario table of one speed and one direction.

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

The technique of the static balance is used in the thrust capability calculations to estimate the thrust configurations at one wind speed but various directions. The objective is to support the wind speed at minimum thrust requirements. The results are given in the form of thrust 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 polar plot.

The defined failure mode considering the failure of the main thruster or any other user-defined limitation is used to rerun the DP capability to present the failure plot in the same plot of the full DP capability to note the difference.

The powering estimation is done with the help of empirical techniques from the balanced thruster configurations. After the suitable power is defined for the desired DP operation of the vessel. All the results are represented in the form of DP capability report.

3.4 Vessel Particulars

3.4.1 Selection of Main Parameters

The process of calculating the DP Capability at the initial design stage must remain satisfied with the handful data available at that early phase. This is a design limitation by itself and predicting reliably from this is a formidable challenge. Thanks to the early works done by a number of researchers to theoretically, experimentally and empirically define the load and behavioural characteristics that the forces can be explicitly estimated from the main particulars and some additional basic parameters.

The main required particulars for the hull are the vessel's length, draft, displacement and block coefficient. The selection of other relevant dimensions depends on the objectives. For example, windage area is required for wind loads, whereas, the underwater projected hull area is required to calculate the current loads. Another important dimension is the centroid of lateral and frontal projected areas since it is required to calculate the moments about the centre of rotation of the vessel.

The inputs are analyzed and matched to relevant data-sets and methods before a numerical calculation is commenced. The number, position, type and operational state of the thrusters must be given as input to optimize the thrust configurations. The input and selection of calculation parameters are discussed under subsection headings in the following pages.

Traditionally, ship input data in terms of measured length are with respect to the Aft Perpendicular. It is the line through the center of ship rudder stock in the longitudinal frame of the ship. For DP calculations, these lengths are changed with respect to the midship since most of the experimental results consider it as the center of rotation and the measured coefficients are presented at this point.

3.4.2 Dynamic Allowance

It is the extra power margin over the obtained results from static capability. As discussed earlier, the dynamic allowance factor takes into account the fact that the forces in nature are not constant but varies in magnitude and direction, so there must be some reserve power to deal with the extra fluctuation or surge in the incident forces. The dynamic allowance is finally used if a time-varying station keeping ability is calculated. In the present static capability calculations, an educated margin as suggested by various papers discussed in the previous chapter is kept. It is taken into account by the following calculation process:

$$\textit{Final Power} = \textit{Power (from Static DP Calculation)} \ X \ (1+\textit{dynamic allowance} \ \%) \qquad (4)$$

DNV-GL recommends the DP Dynamic Allowance to be 25%. So, the final power would be:

$$\textit{Final Power} = \textit{Power (from Static DP capability Calculation)} \ X \ (1.25) \qquad (5)$$

In terms of thrust,

$$\textit{Available Thrust for Static Capability} = \textit{Nominal Thrust}/1.25 \qquad (6)$$

This means that the maximum available thrust for Static DP Capability with 25% of Dynamic allowance is 80% of the Full or Nominal thrust that the thruster is capable.

3.4.3 Maximum Wind Speed

Maximum wind speed serves as an upper limit to optimization calculation. DP plot is represented in terms of wind speed. The current is constant throughout. The wave depends on the corresponding wind speed. Even though the propulsion power is very high, it is simply not practical to indefinitely increase the wind speed. In real scenario, a DP operation will cease to exist in a violent storm or gale winds.

The operational characteristics of the seaway govern the maximum wind taken into account in a DP capability calculation. IMCA-140 suggests that a speed of 50 [m/s] as the upper limit, while DNV-GL thinks that considering the Beaufort-11 at 32.6 [m/s] wind speed is enough. These are suggested limits in formulating DP plot and somewhat more mathematical than real significance. In practice, most of the DP vessels would stop operations over Beaufort-7.

3.5 DP Capability Plot

3.5.1 Type of Polar Plots

DP capability plots define a DP vessel's station-keeping ability under given environmental and operational conditions. The capability plot is often presented as a polar diagram with a number of envelopes, depicting the ship's capability to keep the position in a certain environment with a certain combination of thrusters. The capability plot is often set against a scale of increasing wind speed with a fixed current speed and a fixed relation wind speed and wave height (B. V. Ubisch 2004). The capability plots are divided into two categories:

i) ***Basic Plots*****:** Also termed as the Wind Envelope Plot (IMCA-140 2000), it is the most common type of plot representing the maximum wind speed that can be handled by a station-keeping vessel. The wind angle of attack is considered full from 0 to 360 degrees in steps of 5 to 15 degrees.

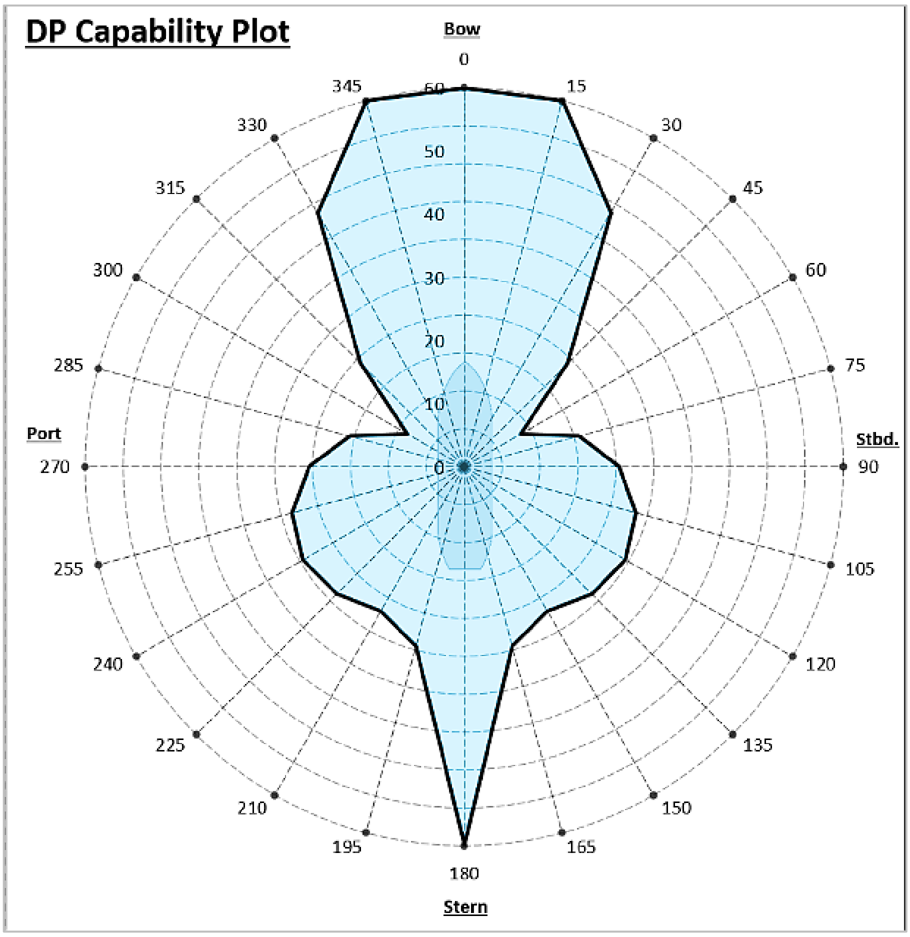

Fig. 10: An example of DP Capability Plot

The wind representation also takes into account the wave drift determined from the wave characteristics due to the wind and a constant current. IMCA additionally recommends the representation of the worst single failure case results in the wind envelope plot.

ii) *Comprehensive Plots*: Also known as Thrust Envelope Plot, this type of plot allow an individual input of wind, current and wave data (in magnitude and direction). It displays the power required for the thruster over 360° heading angle of the vessel, allows the selection of the optimum heading angles and indicates the exact power levels for the thruster which is a valuable tool for the optimized operation of the vessel. It represents the maximum obtainable thruster force for a combination of mean environmental force from wind, wave drift, current and other operational loads (Smogeli 2013).

Capability plot results vary considerably depending on the calculating methods. The main areas of dispute are the different procedures in the calculation of the drift forces, different ways of determination of the thruster efficiency. Model test provides reliable values than the current and drag forces calculated form simple coefficient relations. (Herdzik 2013)

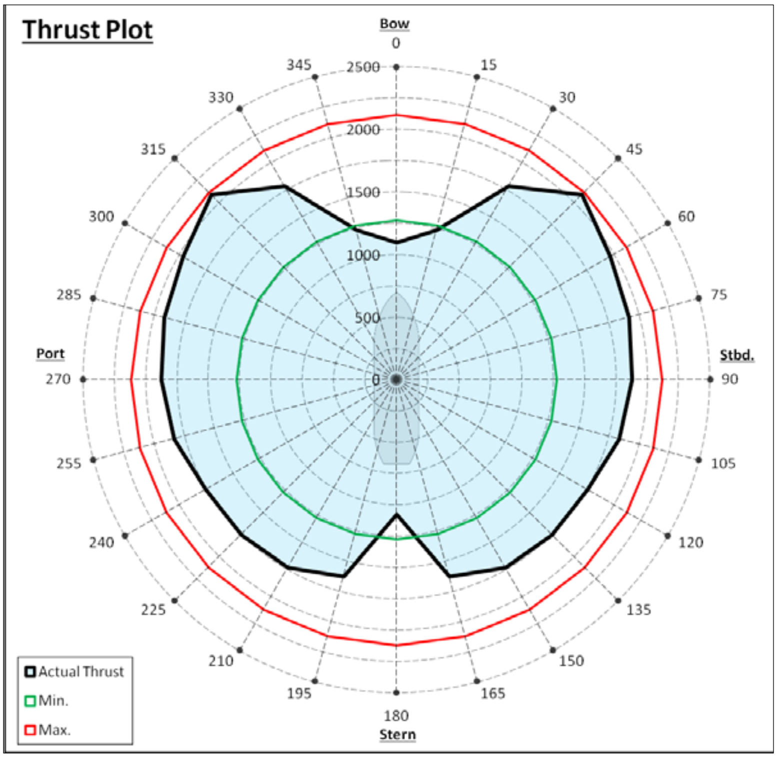

Fig. 11. An example of Thrust plot

3.6 Main Challenges

In contrast to the common boundary conditions in the ship design, the DP capability is relatively hard (Schutte 2016) to predict with engineering accuracy. Due to the high complexity of force models, superposition of ambient forces, ship responses and interactions, it is inherently difficult to estimate or calculate the power requirements and arrangements for a vessel beforehand. Since some of the coefficients vary greatly between themselves, the reliable estimation of the surge, sway and yaw forces for wind, current and wave drift forces is always difficult and must be cross-checked before a decision on the thruster configuration is made.

Excel has a limited capability in terms of handling so many variables together in the optimization process. Therefore, it was difficult in terms of modifying the built-in solver to prepare it for the DP capability estimation. Quite a good number of macros have been generated in or to facilitate the calculation at various stages.

The task is study intensive, meaning that ample time has to be invested in gaining appropriate knowledge, understanding of the problem, developing solving techniques, then implementing coherent procedures, and then gaining more knowledge through the analysis and review of results. This cycle has to be continued until an optimized-reliable path is formulated. There are two progressive stages for estimating the DP capability of a vessel. DP capability is usually evaluated based on static force balance. The ambient forces are assumed constant only at a particular time. However, as the wind and wave direction changes, the balance of forces must also be adjusted by the help of main propellers, thrusters or the hydrodynamic lift from the rudder, thus, leading to dynamic considerations.

3.7 Summary of the technical work

The technical work related to the development of the DP optimization tool has been primarily divided into three main phases:

- The *1st phase* broadly deals with the major concerning factors like modelling environmental loads, static capability analysis, thruster configurations optimization, DP plot calculation and all related knowledge development.

- The *2nd phase* targets fine-tuning and accuracy considering interactions, power assumptions and reliability using validation and evaluation of the developed process.
- The *3rd phase* deals with ease of use of the developed tool and aspects concerning the representation and generation of standard DP capability report. The steps are detailed in the table below:

Table 1: Details of DP capability estimation phases

1st Phase	Background Study: i) Understanding the prediction of ship motion characteristics from initial design data. ii) Further detailed study, reading actual DP design reports and understanding the in-house processes being used in the design and calculation of the DP System. iii) Understanding the environmental effects. iv) Understanding the calculation of the positioning and thruster forces considering interactions. v) Learning software and techniques related to DP calculations and for the presentation of results.
	Design and Formulation: i) Primary Focus: on static force balance with thrusters and ambient effects. Secondary focus: additional ship-borne characteristics input to increase accuracy ii) Finding a working methodology (flow chart) suitable for the formulation of the model and related calculations. iii) Study on the integration of calculation parameters to the initial design data. iv) Primary set-up of the calculation procedure taking into consideration a defined number of thrusters and forces.
2nd Phase	Validation and troubleshooting: i) Sort out useful methods for evaluating wind, current, wave drift and interaction effects if possible. ii) Use of DP design data for already built/working vessels to validate the developed calculation model. iii) Troubleshoot errors considering different aspects and limitations of the calculations. iv) Evaluation and fine-tuning of the calculation modules.
3rd Phase	Development and detailing: i) Standardized-usable representation of the calculation formats that can be used across different projects and ship types. ii) User Manual for the DP Tool

4. EXTERNAL FORCES

Accurate prediction of the external forces is essential in determining the DP capability and thrust configuration of a vessel.The ambient forces are due to wind, current and waves. Moreover, due to the operational characteristics of the vessel, there are additional loads that may act on the vessel. In this section, the process of estimating loads on the ship due to individual loading factors are outlined.

Since the estimation of the loads is part of an optimization tool and the values are to be instantaneously fed into the process for each deviation of the operating variables in order to proceed with the calculation, theoretical, empirical and results from the experimental procedures are used. Procedures requiring analysis or greater data-sets than available at the initial design stage are avoided. The user of the tool has the courtesy of choosing his own method depending on the ship type. More accurate data from the wind tunnel tests or external programs can also be integrated into the form of supplied data.

4.1 Wind

The main factors that determine the wind loads on the ship are the wind speed, direction and the projected area of the ship above water facing the wind. Estimation of the profile affected by the wind comes from the initial GA. The area that may increase due to the addition of temporary structures in case of various operations like trenching or cable laying is taken into account. Moreover, if the vessel has two operational drafts, the calculation is done for both the drafts.

The calculation takes into account that the wind speed is non-fluctuating about the selected mean. The projected area is derived from the frontal and lateral projected area of the ship. The center of each of the area needs to be derived since the wind load is considered to be acting about this point. The moment is calculated with respect to this point about midship. The vertical position of the centroid determines the effective wind speed that needs to be considered to be acting on the body. As suggested by IMCA (IMCA-140 2000), average wind speed, as well as the coefficients, are taken into account considering that this centroid is 10 meters above the waterline. Any increase in the vertical centroid must be compensated with suitable height multiplication factors. The average wind speed is considered to be the one minute mean approximated by a value of 1.15 times the hourly mean.

Table 2: Wind force height coefficients (for one-minute wind speed, IMCA-140)

Meters Height of Centroid Over – Not Exceeding	**Height Coefficient, C_h**
0-15.3	1.00
15.3-30.5	1.18
30.5-46.0	1.31
46.0-61.0	1.40
61.0-76.0	1.47

4.1.1 Wind load coefficients

The surge, sway and yaw coefficients, as described before, comes from different experimental, empirical and theoretical data. Deriving of the coefficients from wind tunnel experiments for a ship at a particular wind speed and angle come from:

Surge Coefficient,
$$Cwx = \frac{Fwx}{\frac{1}{2}\rho_a Vw^2 A_F} \tag{7}$$

Sway Coefficient,
$$Cwy = \frac{Fwy}{\frac{1}{2}\rho_a Vw^2 A_L} \tag{8}$$

Yaw Coefficient,
$$Cwn = \frac{Mwn}{\frac{1}{2}\rho_a Vw^2 A_L . L_{BP}} \tag{9}$$

The methods used in the tool to get the wind coefficients are described in Table 3. All these methods give the variation of the wind coefficients with respect to the change in the angle of incidence from 0 to 360 degrees.

Table 3: Methods to get the wind load coefficients in the DP tool

Methods	**Description**
Supplied Data	Using Manual Supplied force and moment coefficients
IMCA	Using the guidelines of IMCA-140
Blendermann	Using coefficients collected from wind tunnel tests from Blendermann
Isherwood	Using coefficients derived from experimental results from Isherwood
DNV-GL	Using formula from DNV-GL DP Standard
Gould	Using coefficients derived from experimental results from Gould
OCIMF	Using coefficients derived from OCIMF (VLCC) database

The supplied data comes from user input depending on experience, similar vessel data, or wind tunnel experiments. The corresponding load calculation is a straight-forward from the input data, using the wind velocity and the given areas.

The methodology of the wind load calculation comes from IMCA-140. The empirical formulae described in the method can also be used to determine the coefficients. Additionally, IMCA describes shape coefficients for superstructures that are used for calculating the projected area of various exposed parts. Moreover, it suggests that the isolated superstructures are to taken into account individually, while the shielding effect and the blocked area for several deckhouses or structures to be assessed using a combined shape factor.

Table 4: Shape factors for exposed areas to wind suggested by IMCA-140

Exposed Area	**Cs**
Cylindrical shapes	0.50
Hull (surface above waterline)	1.00
Deckhouse	1.00
Isolated structural shapes (cranes, channels, beams angles)	1.50
Under deck areas (smooth surfaces)	1.00
Under deck areas (exposed beams and girders)	1.30
Rig derrick	1.25
Blocked in projected area of several deckhouses	1.10

The wind load coefficients from the systematic collection of wind tunnel test data is obtained from the paper of (Blendermann 1996). (Isherwood 1972) uses multiple parametric regression techniques to fit experimental data from merchant ships. (DNV-GL 2015) recommends their own theoretical formulae for the calculation of the wind loads. (Gould 1982) details numerical procedures for the calculation of forces and moments at effective wind speed that is assumed to be varying logarithmically with the increase of height from the sea surface. (OCIMF 1994) uses the actual results from their database to predict the wind loads in Very Large Crude Carriers (VLCC). The choice of applicable method depends on the ship type and size. The wind surge, sway and moment coefficients for a vessel for all the selected methods are presented in the graphs below:

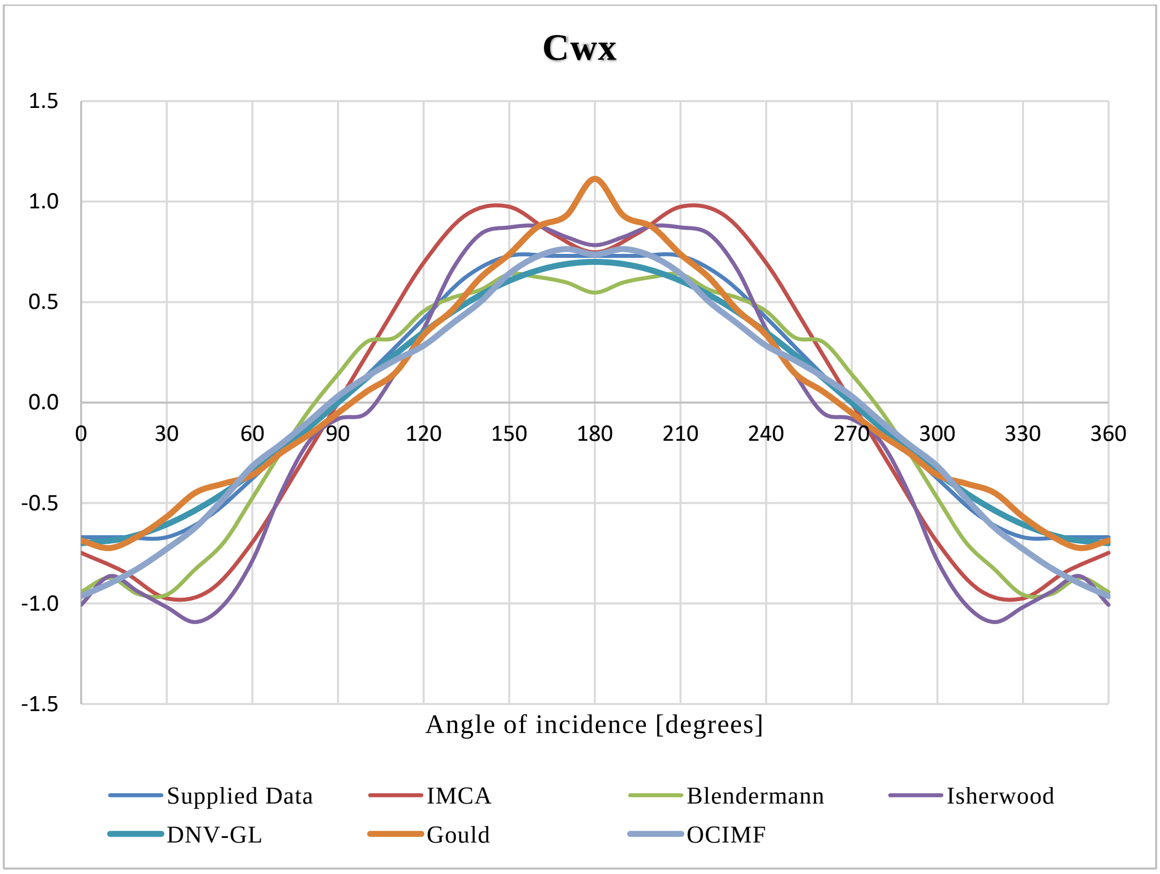

Fig. 12: Variation of the wind load surge coefficients with incoming angles for different methods

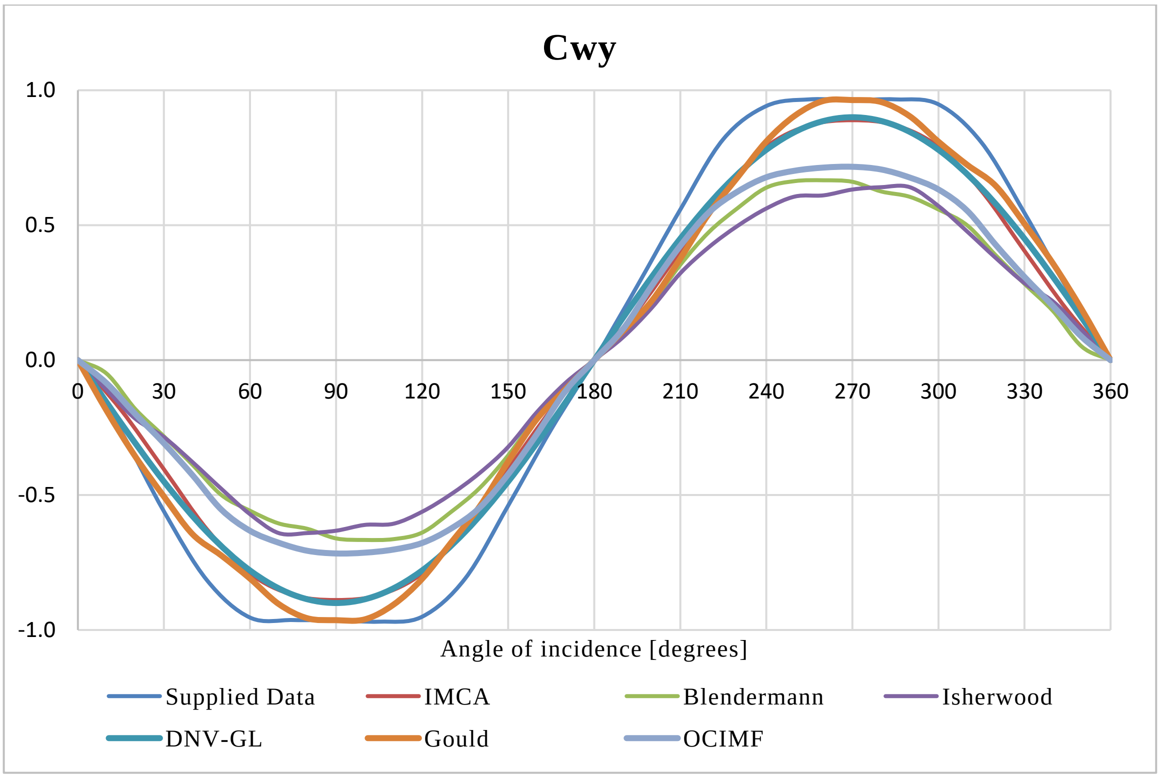

Fig. 13: Variation of the wind load sway coefficients with incoming angles for different methods

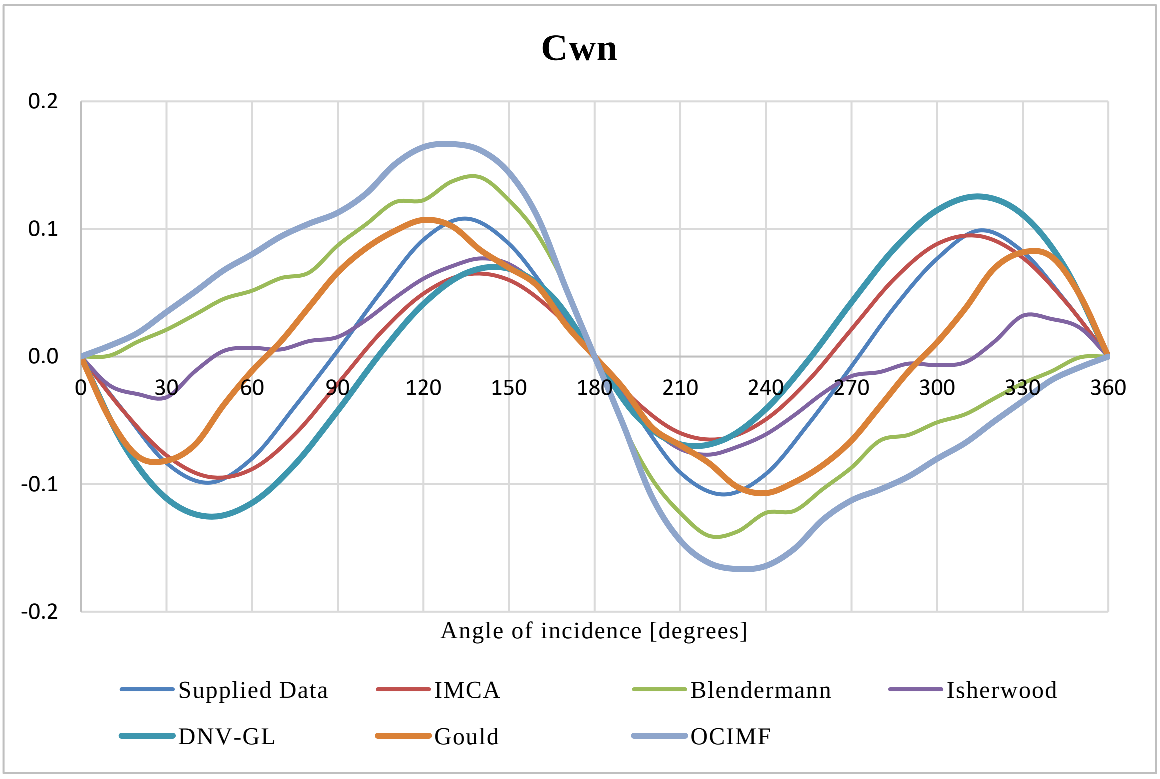

Fig. 14: Variation of the wind load yaw coefficients with incoming angles for different methods

The graphs in Fig. 12, Fig. 13, and Fig. 14 show that the coefficients for each of the load calculations vary among the methods. However, the trend is similar to all graphs except the yaw coefficients coming from Blendermann and OCIMF in the 0~90 degree ranges.

The calculation of the loads from the coefficient is the reverse process of the calculation of coefficients from experimental loads and are presented by the following formulae:

Wind Load at particular speed Vw and direction ϴw:

Surge Load, $$Fwx = \frac{1}{2}\rho_a Vw^2 A_F . Cwx \quad (10)$$

Sway Load, $$Fwy = \frac{1}{2}\rho_a Vw^2 A_L . Cwy \quad (11)$$

Yaw Moment, $$Mwn = \frac{1}{2}\rho_a Vw^2 A_L . L_{BP} . Cwn \quad (12)$$

Further details including tables, corresponding formulae and calculation parameters are presented in the Appendix as a reference. The wind load for a multipurpose vessel is presented in the DP Capability Estimation chapter as an example of the actual calculation procedures.

4.2 Current

The underwater hull form is responsible for the current load on the vessel. Only the length, breadth, draft or underwater transverse and longitudinal area and their centroid are relevant in the estimation of current loads in the initial ship design stage.

It is IMCA and DNV-GL recommendation to consider a constant speed for the current and coincident direction to that of wind. IMCA suggests for a constant current speed of 1 knot and DNV-GL suggest constant current speed according to the following table:

Table 5: Current speed corresponding to Beaufort number recommended by DNV-GL

Beaufort (BF) No.	Beaufort Description	Wind Speed [m/s]	Current speed [m/s]
0	Calm	0	0
1	Light air	1.5	0.25
2	Light breeze	3.4	0.5
3 and above	Gentle breeze and above	5.4 and above	0.75

Several methods are available to be used in the tool in order to estimate the current loads in floating structures. Similar to the technique used in the wind load estimation, empirical, theoretical or experimental values are taken from different papers in terms of current load coefficients for the surge, sway and yaw. The supplied initial data is used to estimate the current load at constant current speed. The methods used in the tool are described briefly in the following paragraphs. More details including the corresponding data tables and formula are given in the Appendix. The coefficients from Supplied or manual data inputs come from experience, similar vessels, wind-tunnel tests, CFD or simulation tools. This is included to allow the DP capability current load estimation process more flexible. An example of manual data input for the surge, sway and yaw coefficients for a cruise vessel has the following variation in the incoming current direction:

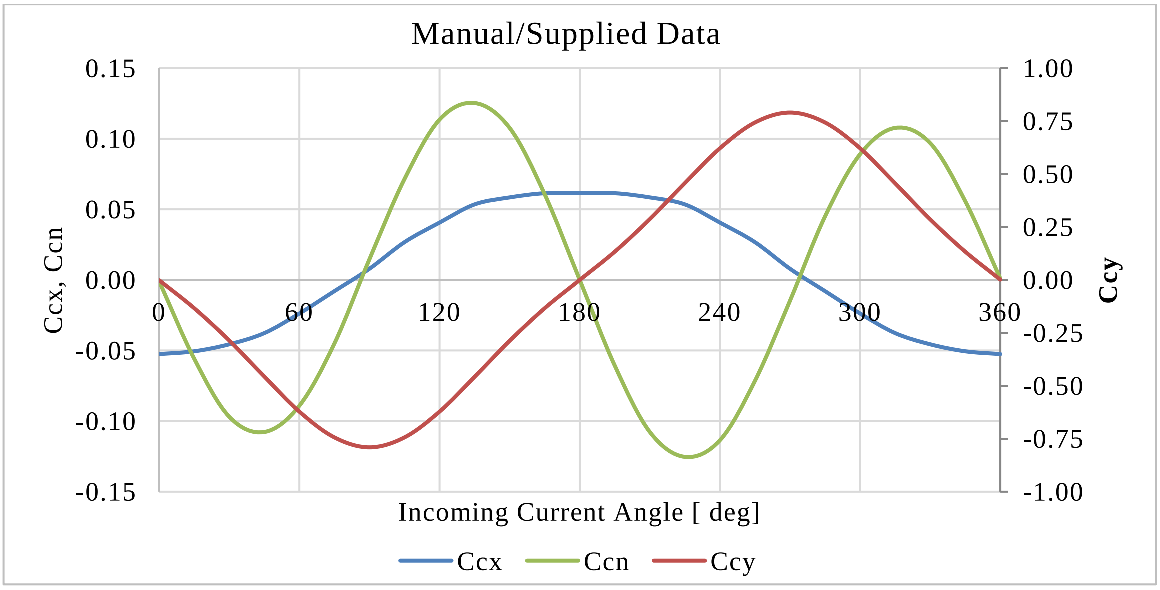

Fig. 15: Experience based current surge, sway and yaw coefficients data for cruise vessel

IMCA suggest the current loads to be calculated from the coefficients obtained from the work of (Nienhuis 1987). In the paper, the coefficients are presented for five types of vessels, namely, supply vessel, ferry, container ship, tanker and drillship. The load values are estimated from the coefficients at the particular angle of incidence from the nearest matching vessel.

The coefficients for the vessels are represented in the graphs below. It is seen that the general trend for all the vessels is similar. The variation of the values is because of the type of the vessels considered. The relevant formulae, values and graphs are presented in the latter part for a more detailed representation of the process.

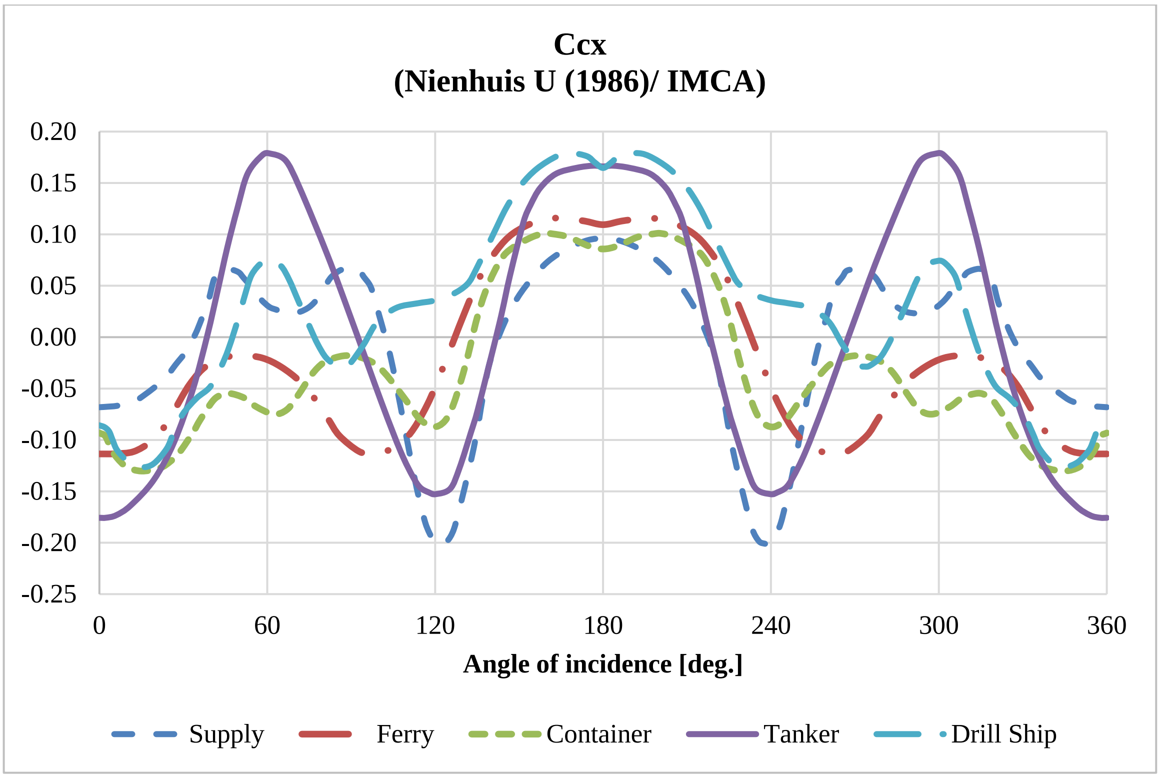

Fig. 16: Variation of the current surge coefficients with the change of angle of incidence for different vessels (IMCA)

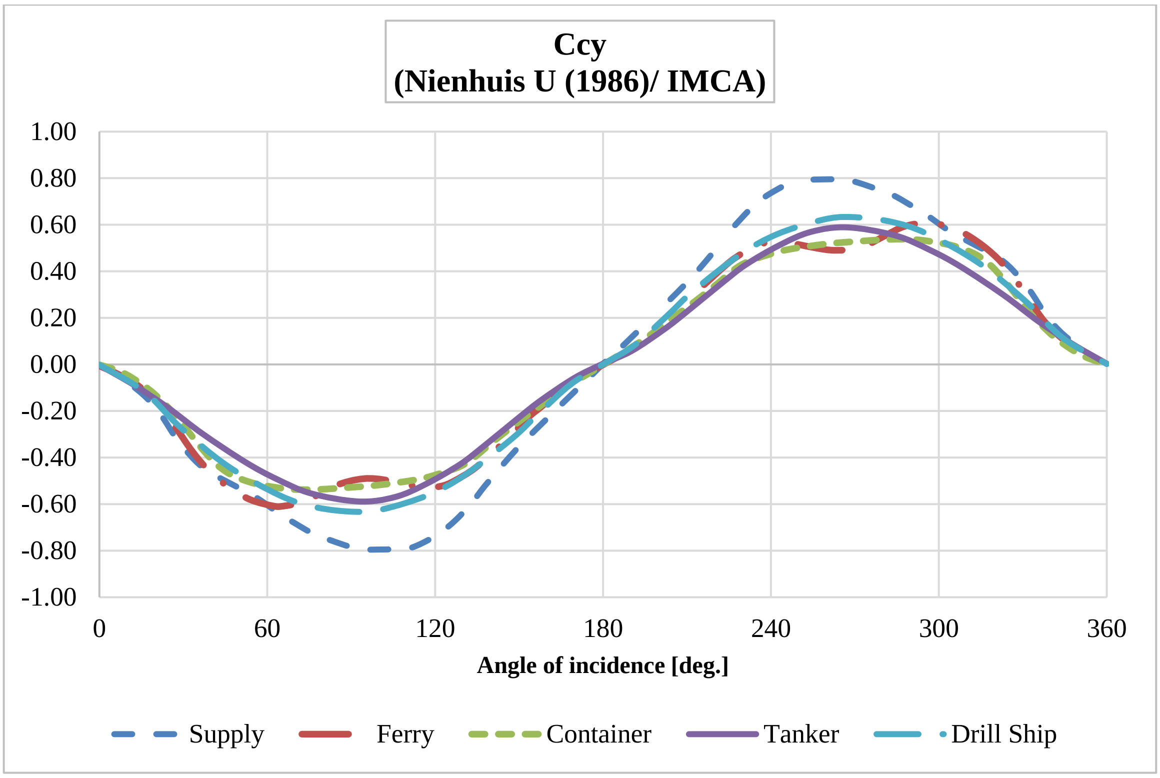

Fig. 17: Variation of the current sway coefficients with the change of angle of incidence for different vessels (IMCA)

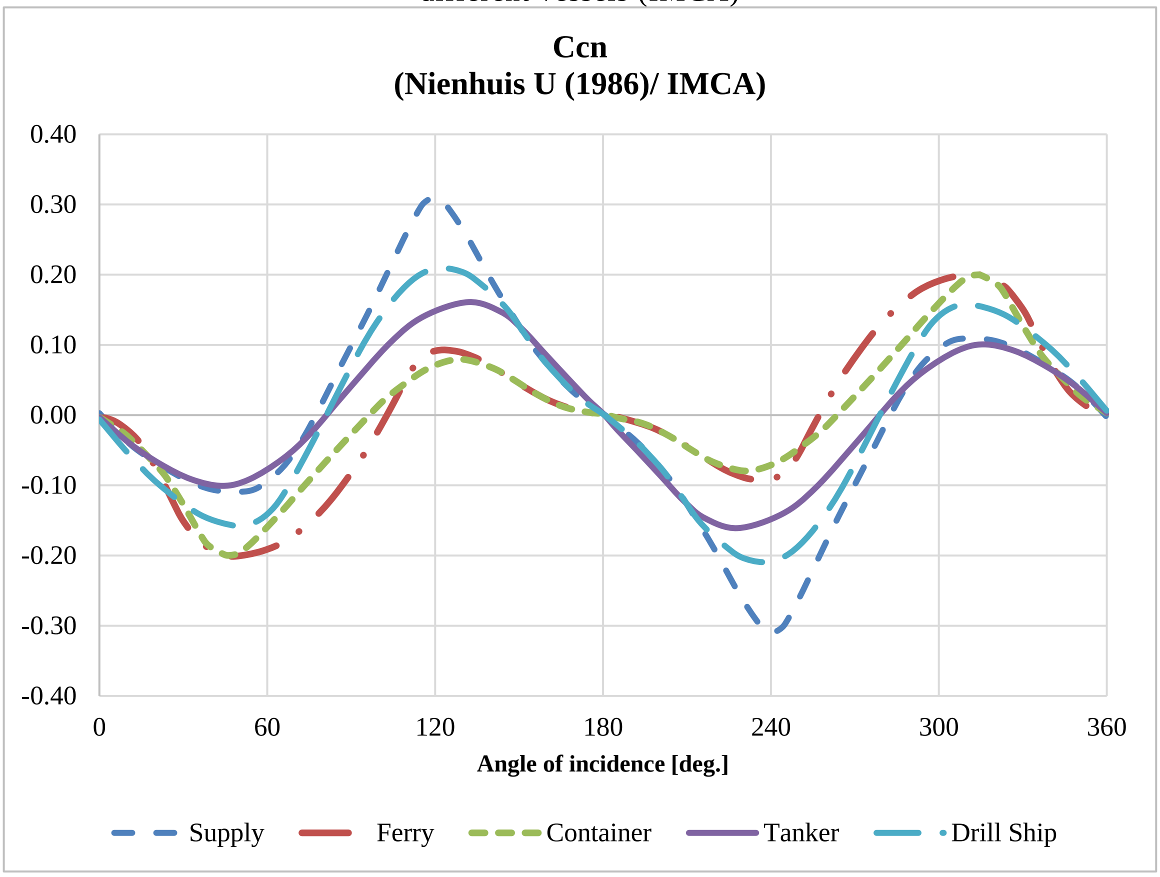

Fig. 18: Variation of the current yaw coefficients with the change of angle of incidence for different vessels (IMCA)

DNV-GL have their own empirical formulae to estimate directly the force and yaw values. OCIMF deals with the current coefficients for VLCCs. At a more advanced stage of the calculation, for reference or cross-checking, if the current loads can be obtained from external strip theory calculations, their values can be given as input in the tables related to strip theory to adopt the process in the capability estimation.

Table 6: Methods with descriptions for the current loads in the DP capability estimation

Current	
Supplied Data	Using Manual Supplied force and moment coefficients
IMCA (Nienhuis)	Using the guidelines of IMCA (additionally, this method has the benefit of choosing any of five vessels: Supply, Ferry, Container, Tanker, Drillship.
DNV-GL	Using formula from DNV-GL DP Standard
OCIMF	Using coefficients derived from OCIMF (VLCC) database
Strip Theory	From external program employing the strip theory

The current loads are calculated from the respective coefficients using the following formulae:

Current Load at constant current speed Vc and direction same as ϴw:

Surge Load,

$$Fcx = \frac{1}{2}\rho_w Vc^2.B.T.Cwx \quad (13)$$

Sway Load,

$$Fcy = \frac{1}{2}\rho_w Vc^2 A_L.L_{BP}.T.Cwy \quad (14)$$

Yaw Moment,

$$Mcn = \frac{1}{2}\rho_w Vc^2 A_L.L_{BP}{}^2.T.Cwn \quad (15)$$

4.3 Waves

As described before, the estimation of the wave load for the ship takes two steps. In the first step, the corresponding wave height and crossing period are estimated from the tables showing wind-wave correlations. Then these values are used with the respective coefficients to find the corresponding wave loads.

The process is inherently complex, both in terms of formulation and correctly quantifying the coefficients. A set of empirical methods is used but the accuracy is often not guaranteed. A detailed study identifies the estimation of the wave load as the weakest link in the process of the DP capability estimation. Since there are a lot of affecting parameters and underlying factors that cannot be addressed simultaneously within the excel platform of the DP tool, a more simplified approach that allows a good approximation is used.

4.3.1 Wind-wave correlation

Any of the two recommended methods, one by IMCA and another by DNV-GL can be used to estimate the wave height corresponding to the wind speed. The relation comes from the fact that waves are driven by the wind. In the DP tool, with the increase in the wind speed variable to test the capability of thrusters to negotiate the loads, there should be an increase in wave height corresponding to a developed seaway. The estimation of the height as well as the wave crossing period is different for different regional spectrums that are available and depends on the operational location expected for the vessel.

Table 7: Wind-wave correlation techniques for the assumption of wave height and crossing period

Methods for determining wave height from wind speed
1. Wind Dependant: North Sea Correlation (IMCA recommendation)
2. Wind Dependant: World Wide Scatter Diagram (DNV-GL recommendation)

IMCA considers the North-Sea correlation data presented in Table 24 in the appendix. The data also includes the effect of swell which tends to be around 1 meter. DNV-GL bases their correlation on the Pierson Moskowitz developed spectrum with $\cos^2$ spreading and 95% confidence interval found from the world-wide scatter spectrum. The relational data of the wind to wave height and crossing period is represented in Table 25 in Appendix.

The selected method give the significant wave height, peak and crossing periods for the waves, wave encountering frequency and also the respective current speed

(DNV-GL method). The available data for both the methods within the have maximum measurable values within practical ranges. For the wind speeds higher than the tabulated values, a linear extrapolation applies (IMCA) for finding the respective wave height and crossing period values. This extrapolation is represented in the following graphs and is of mathematical importance rather than practical significance.

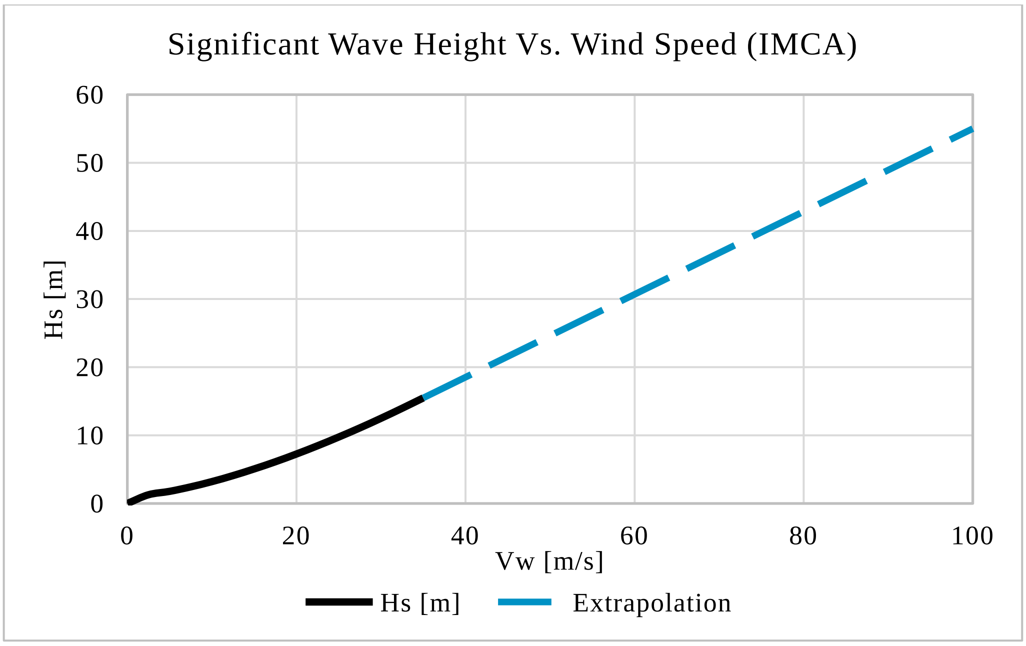

Fig. 19: Representation of wave height to wind speed from IMCA table and its extrapolation

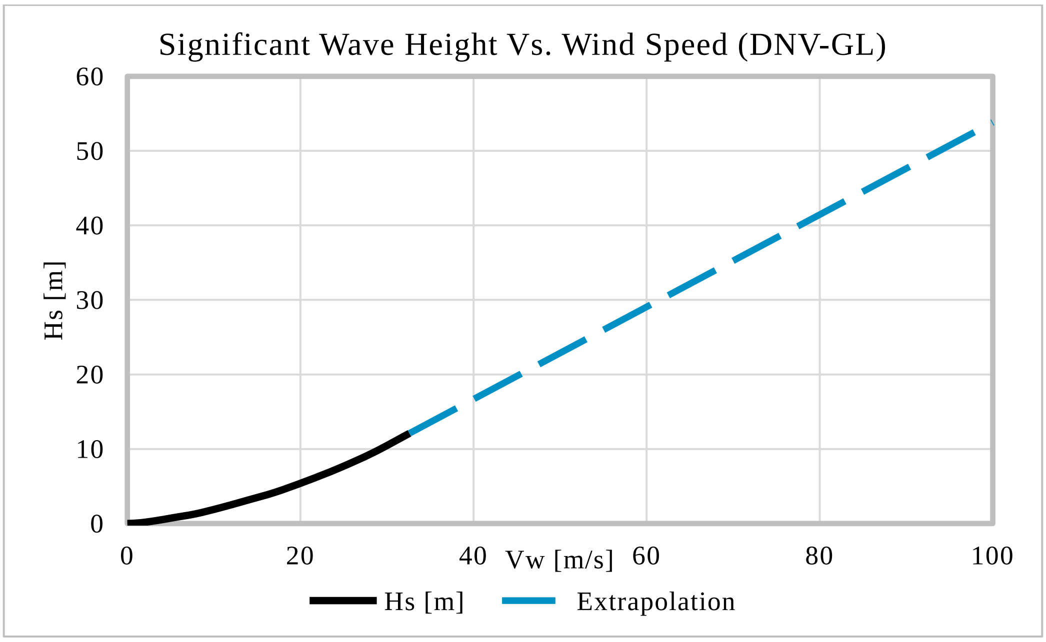

Fig. 20: Representation of wave height to wind speed from DNV-GL table and its extrapolation

4.3.2 Wave coefficients and Forces

The main parameters required at the initial ship design stage for the calculation of second-order wave drift loads are wind speed, significant wave height, wave encountering frequency, the angle of incidence, volume displacement, and the longitudinal centroid of the underwater hull. The coefficient varies with the hull form, so it is difficult to estimate with accuracy for a particular hull the exact wave load for an ambient wave. These loads are also fluctuating, but it is assumed that the methods used in the estimation of loads give a mean value that can be used in the DP capability static load balance.

Table 8: Methods for calculating the wave forces

Wave: Applicable methods	
Supplied Data	Using Manual Supplied force and moment coefficients data
DNV-GL	Using relations given in DNV-GL DP Standard. The wave height must also be derived from Worldwide scatter diagram if this is chosen
Model Scaling	Using data from similar model/ships and employing scaling methods as suggested by IMCA
Strip Theory	Wave drift loads from external program employing the strip theory
Theoretical	Simplified estimation for large floating structures

The methods of estimation include user-supplied data that can be obtained from experience with sister vessels or vessels of the same type. It is to note that the value for each coefficient varies with the wave encountering frequency as well as the encountering angle. Tabulated values as such given in Appendix represent only the values at 15-degree intervals which are used to linearly interpolate for the values in between. The surge, sway and yaw coefficients for a tanker is shown in the form of graphs below:

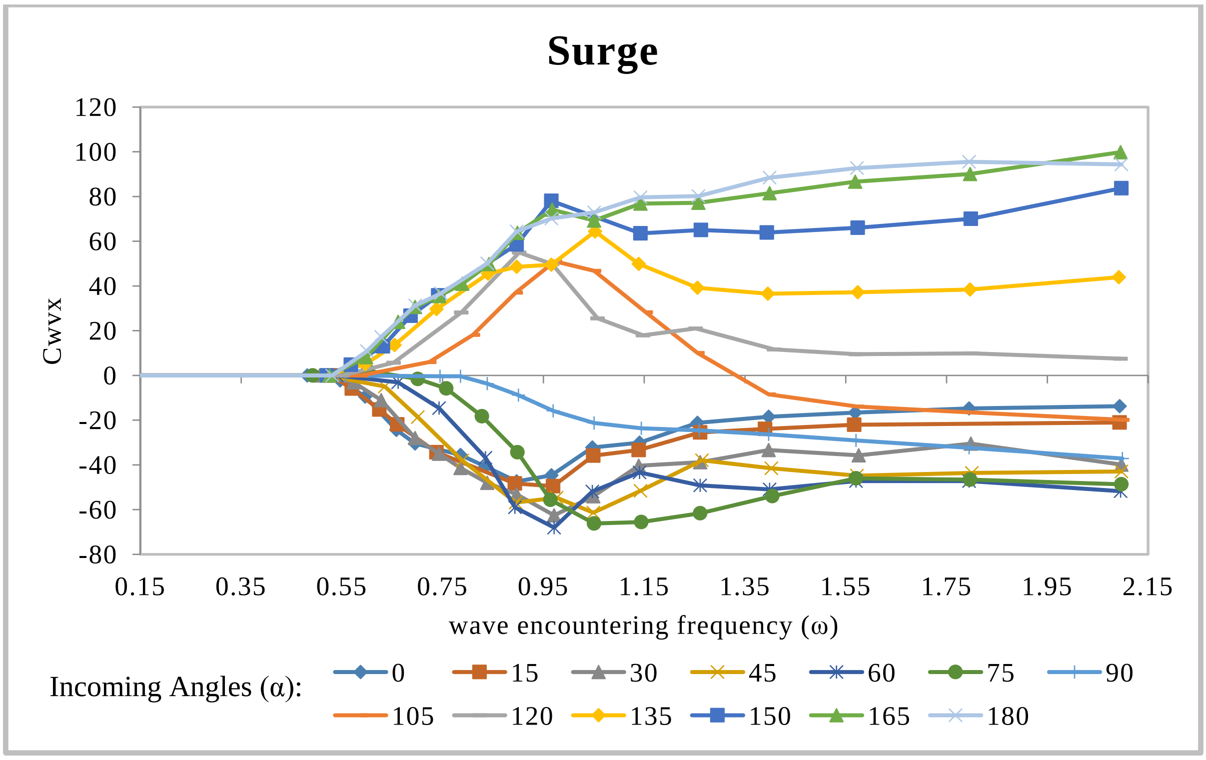

Fig. 21: Surge Coefficients with variation of wave encountering frequency at different incoming angles

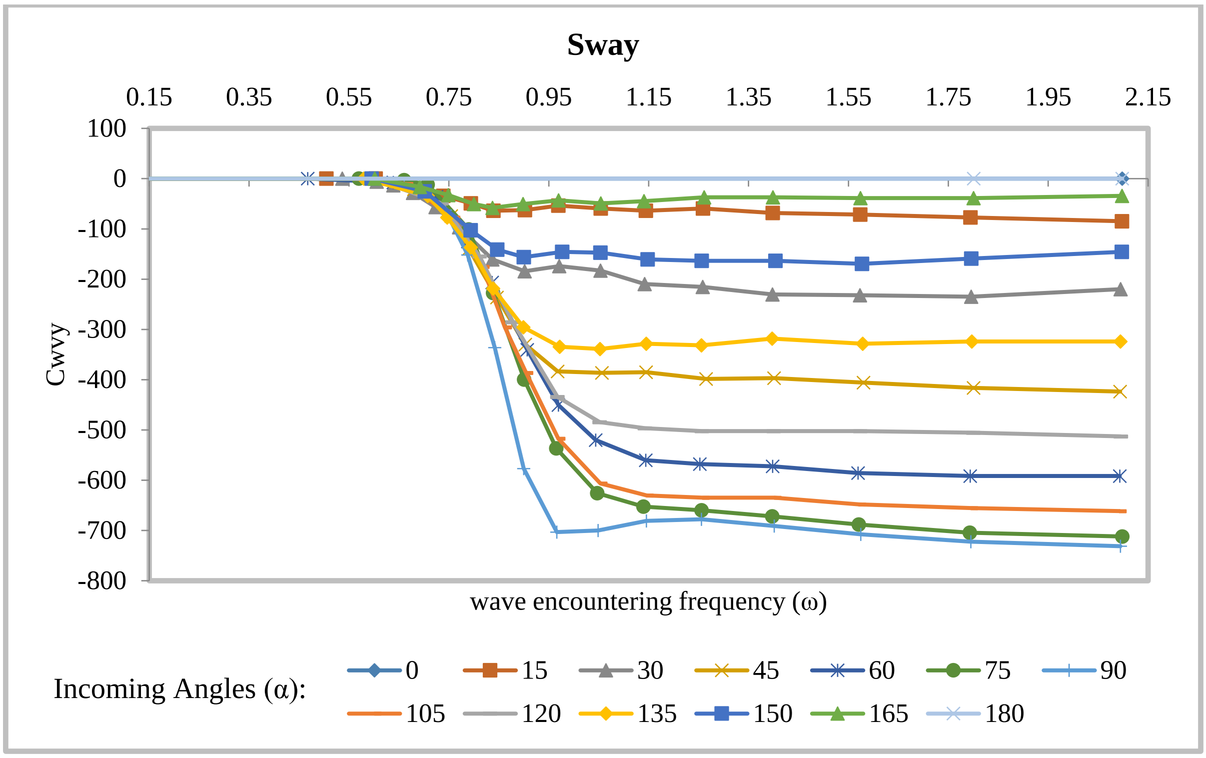

Fig. 22: Sway Coefficients with variation of wave encountering frequency at different incoming angles

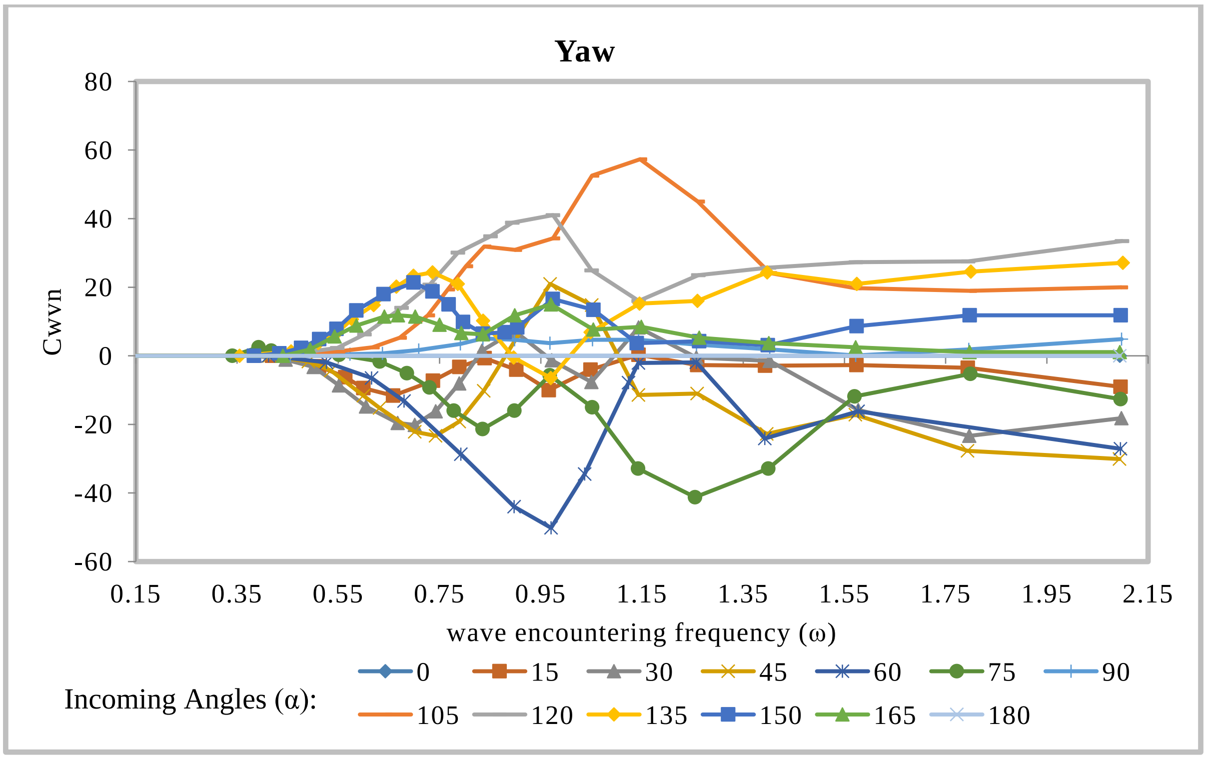

Fig. 23: Sway Coefficients with variation of wave encountering frequency at different incoming angles

The wave loads are calculated from the coefficients using the following formulae:

Wave drift forces at wave amplitude A and direction α same as ϴw:

Surge Load, $$F_{wvx} = \frac{1}{2} g\rho_w A^2 . \nabla^{\frac{1}{3}} . Cwvx \quad (16)$$

Sway Load, $$F_{wvy} = \frac{1}{2} g\rho_w A^2 . \nabla^{\frac{1}{3}} . Cwvy \quad (17)$$

Yaw Moment, $$M_{wvn} = \frac{1}{2} g\rho_w A^2 . \nabla^{\frac{2}{3}} . Cwvn \quad (18)$$

The amplitude ‘A’ if found from mean wave height H which is estimated from the significant wave height using the empirical relations like those suggested by Nordenström (1973), using spectral properties (Journée 2000), or simply multiplying Hs by 0.64 (Juneau 2017).

IMCA suggest using scaling techniques from data of similar ships by non-dimensionalised frequency using wave encountering frequency and the volume displacement of the reference hull:

$$\boldsymbol{\omega' = \omega\sqrt{\frac{\nabla^{\frac{1}{3}}}{g}}} \tag{19}$$

The model is scaled back to the required hull by using the underwater volume of the required hull. IMCA also require the use of the wind wave correlation data from the North Sea. DNV-GL suggest their own empirical formula for the calculation of the wave surge, sway and yaw loads. The details of the formulae are given in Appendix.

The formulae use Hs from the worldwide wave spreading with Pierson Moskowitz scatter diagram. Extra parameter required for the calculation is the longitudinal position of the half of water-line length, the aft water plane area coefficient and the bow entrance angle. The variation of the obtained loads across the encountering angle and wave crossing periods for a multipurpose vessel take the following shapes:

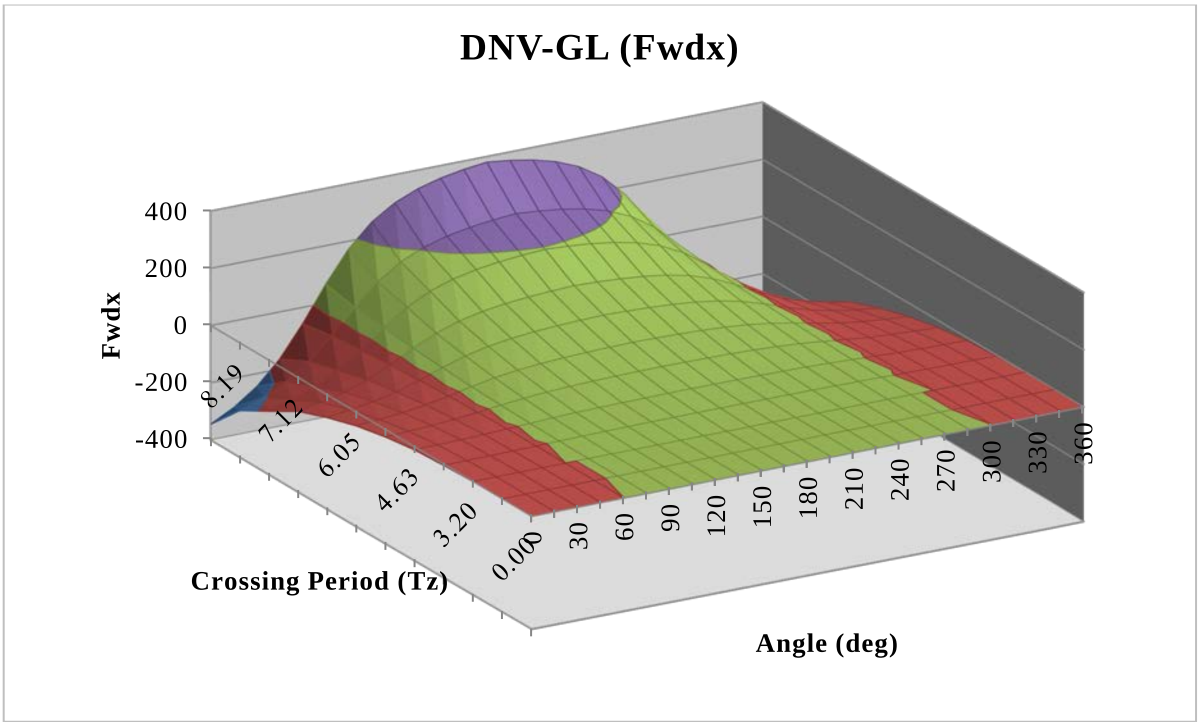

Fig. 24: Variation of wave surge load w.r.t. crossing periods and encountering angles

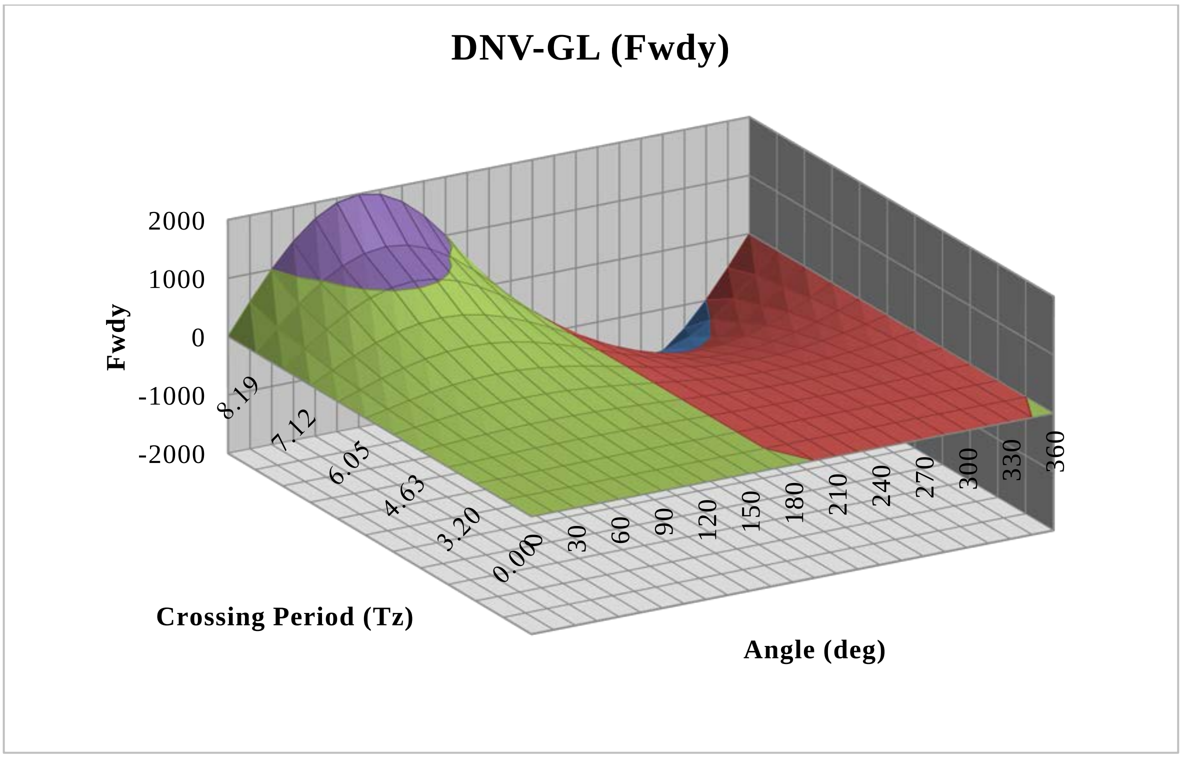

Fig. 25: Variation of wave sway load w.r.t. crossing periods and encountering angles

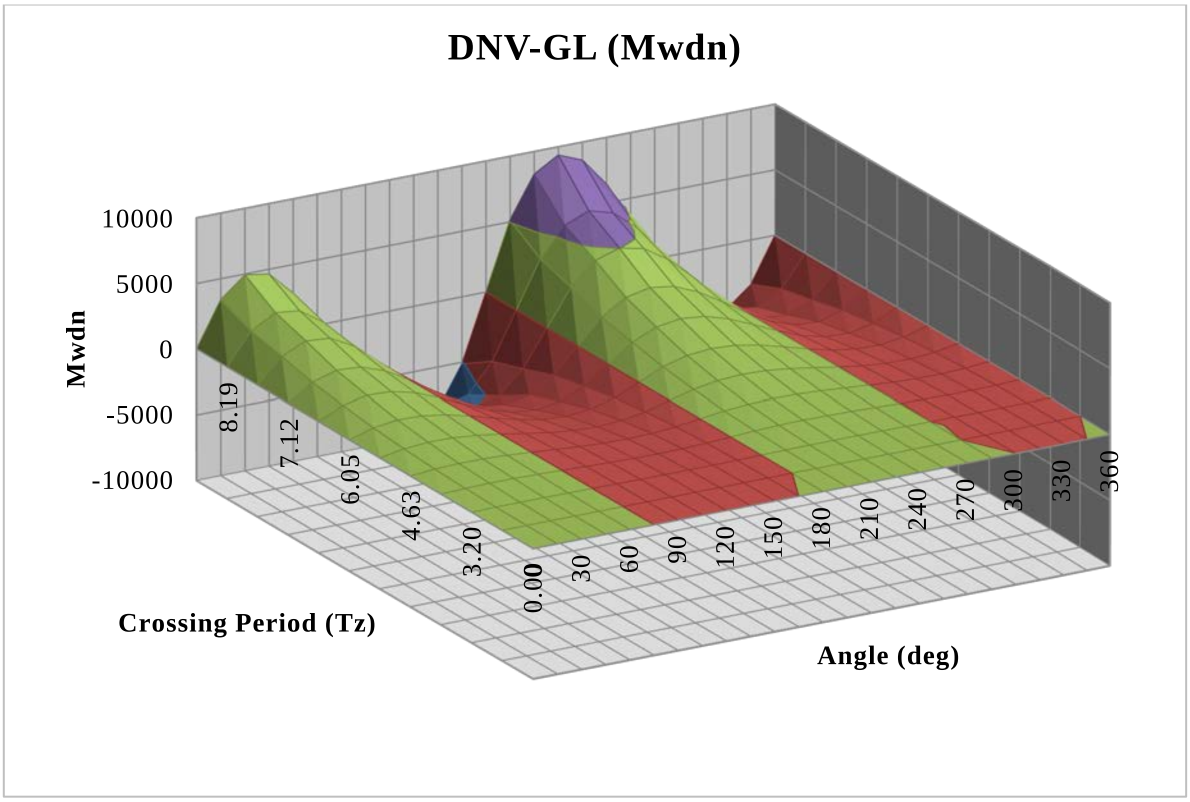

Fig. 26: Variation of wave yaw moment load w.r.t. crossing periods and encountering angles

The theoretical estimation of the wave loads is effective for large offshore structures which behaves as if the wave is being incident on a wall (Journée 2000). This method provides a quick estimation of the estimated wave load on the large floating structure.

4.4 Additional Forces

Additional forces come from operational modes like towing, drilling, pipe-laying, oil transfer, offshore support etc. These are all external forces other than of natural origin that is considered acting continuously on the vessel due to its operation. These forces can be large and are outside the range considered within the dynamic allowance. Since the work only deals with static balance, only mean continuous load in excess of ambient loads are considered. Short bursts or fluctuating loads are handled in propulsion characteristics of the vessel and may be covered by the dynamic DP range.

The combination of the operational loads considered to be acting on a point and can be resolved into its surge, sway and yaw components depending on the direction and centroid of action from amidships. These additional loads are then added respectively with the surge, sway and yaw components due to the wind, current and wave.

4.6 Resultant Components and Actual Forces

The individual loads in terms of surge, sway and yaw from the ambient wind, current, wave and additional operational loads must be added together to find the total surge, sway and yaw loads that have to be handled by the thrusters. This gives the resultant components of the resolved directional forces and moments.

Resultant Load Components:

Total Surge Load, $$F_x = F_{wx} + F_{cx} + F_{wvx} + F_{addx} \quad (20)$$

Total Sway Load, $$F_y = F_{wy} + F_{cy} + F_{wvy} + F_{addy} \quad (21)$$

Total Yaw Moment, $$M_Z = M_{wn} + M_{cn} + M_{wvn} + M_{wn} \quad (22)$$

Actual forces are the magnitude actual wind, current or wave forces acting on the body at the incident angle found from the resultant of the surge and sway components. Since wind, wave and current are considered to be acting from the same direction, the addition of the respective actual forces give the total ambient force acting on the vessel. They are calculated from the following formulae:

Actual Loads acting at ϴ=ϴw=ϴc=ϴwv:

Wind Load, $$F_{WR} = \sqrt{{F_{wx}}^2 + {F_{wy}}^2} \quad (23)$$

Current Load, $$F_{CR} = \sqrt{{F_{Cx}}^2 + {F_{Cy}}^2} \quad (24)$$

Wave Load, $$F_{WVR} = \sqrt{{F_{WVX}}^2 + {F_{WVY}}^2} \quad (25)$$

Total Load at ϴ, $$F_R = F_{WR} + F_{CR} + F_{WVR} \quad (26)$$

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5. THRUSTERS

There can be a variety of thruster types that a vessel may employ for propulsion and manoeuvring. While the main function of the propulsion system is to supply adequate thrust to propel the ship towards its destination at the desired speed, in DP, thrusters have an additional function related to manoeuvring, static force balance in maintaining the position and heading. This means that the thrusters in DP are also used in station keeping of a vessel about a desired or fixed position. This extra expenditure of energy even when the vessel is moving the least, is clarified by the fact that external forces always in a seaway, irrespective of the motion of the vessel itself.

At the initial design stage, the type of the propulsors to be used in a vessel can be checked for their DP capability depending on the power, directional flexibility, positional suitability, and interaction effects. Each thruster type has its own advantages, constraints and optimum operational range.

The excel DP optimization tool has the capability of handling 16 different thrusters working individually or in combination. This number is not a design limitation of the solver but only a practical consideration. The main types that are handled are transverse thrusters, azimuth thrusters, and propeller-rudder combination, as these are the most conventional propulsor used in the DP vessels. Other types, as well as non-conventional forms of devices, can be easily integrated by knowing the design power and directional characteristics and variation of the nominal thrust.

Two things are important here: one is the thruster capacity and the other is the thrust management. While the estimation of the maximum thrust requirement is enough in thruster capacity, thruster management deals more with the balanced use of the available power. Thruster management comes into effect when deciding the share and usage of a thruster for incident unidirectional loads. The optimizing goal is, therefore, to successfully negotiate the load with the least possible expenditure of energy.

5.1 Transverse thrusters

As the name suggests, transverse thrusters provide thrusts in the transverse direction only. They are also called tunnel thrusters because of the ducted impeller flow across the vessel. The tunnel thrusters at the bow are known as bow thrusters whereas the thrusters at aft or stern skegs are called stern thrusters. Generally, there are more than one of the individual types of transverse thrusters present in a DP vessel. Transverse thrusters act to negotiate the sway component of the external forces on the vessel. Most of this thruster can work with same efficiency in forward and reverse thrust directions. However, some stern thrusters, in order to avoid the blowing in of water to the hull have reverse thrust restrictions.

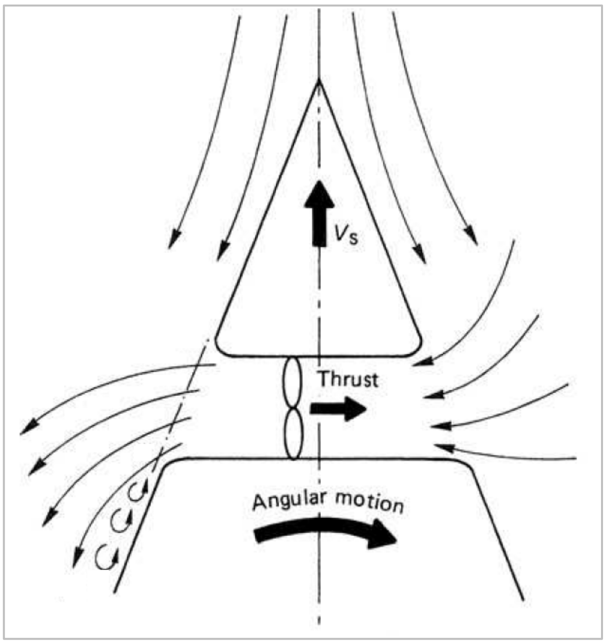

Fig. 27: Transverse propulsion unit thrust and angular motion (Carlton 2007)

The transverse thrusters work most effectively if the vessel is stationary in comparison to the surrounding fluid (English 1963). Other affecting factors are the vessel speed, cross current, tunnel length and turbulence, the fairing of the tunnel openings etc. While the study of the tunnel thrusters and their interaction mechanisms is a vast field by itself, only the thrust outputs calculated using empirical methods considering the vessel steady will be used in the present DP calculations.

The main variables considered in the calculation of thrust and moments are the designed power of the thrusters, their longitudinal positions from aft perpendicular and the transverse distance from the centerline of the ship. The designed excel tool has the capacity of handling a combination 6 transverse thrusters.

5.1.1 Estimation of thrust for Transverse Thrusters

IMCA recommended empirical multiplication factors or DNV-GL formulation can be used to estimate the thrust from the power of the transverse thrusters and vice versa. The dynamic allowance determines the maximum power or thrust that can be utilized only by the static DP capability calculations.

IMCA suggests a value of 11 kg/hp for the estimation of thrust. This value also accounts for the relevant tunnel loss while mentioning that the thrust degradation associated with the cross-current flows can be ignored. Unless the thruster manufacturers specifically mention otherwise, the transverse thrusters are considered to give identical thrusts in the positive and negative directions.

DNV-GL estimation of thrust for the transverse thrusters takes into account 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 details of the estimation of the thrust from power for each process is presented in the Appendix.

5.3 Azimuth thrusters

This includes Z-drive thrusters and podded propulsors. Azimuth thrusters are highly used in the DP vessels mainly due to the directional flexibility of the thrust output and steering ability at low speeds. Multiple units can easily act together to form a DP capable configuration. The generated thrust highly specific to the intended direction and need not to be balanced by other means as can be seen in case of a forward thrusting propeller with rudder generating side force. Variable pitch azimuth drives add yet another variable to the optimization parameters.

Thrusting in the positive direction is usually desired and can be achieved by direction control. Reverse thrusting an azimuth thruster cause a significant loss of thrust efficiency. Another important issue to be considered is the interaction effect between the thrusters which will be discussed later.

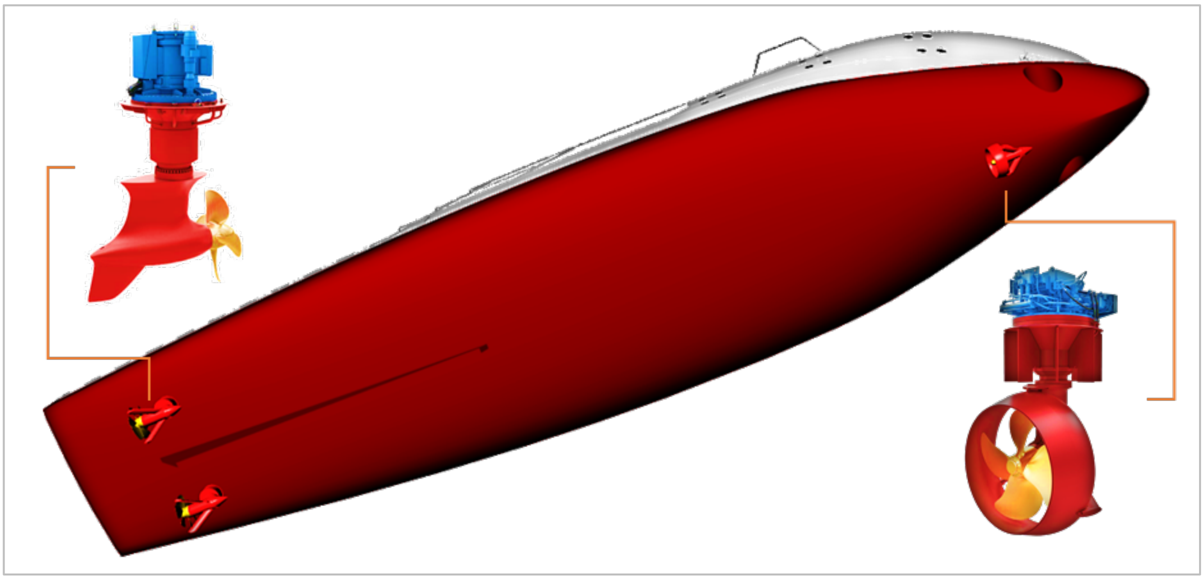

Fig. 28: Azimuth thruster typical locations in a DP vessel

The longitudinal and the transverse position, power, forward and reverse thrust ranges, minimum and maximum operating angles are generally the required inputs for thrust configuration calculation in the DP capability estimation. In the developed excel tool, there can be six different azimuth thrusters that can be taken into account simultaneously, and once again, this is not a tool or optimization limitation, but a practical consideration.

5.3.1 Estimation of the directional thrust for Azimuth Thrusters

The thrust or the power for the azimuth thrusters are empirically determined using IMCA suggested factors or DNV-GL methods. The thrusters are able to produce directional thrusts in forward and reverse directions. IMCA gives a value of 13 kg/hp of thrust for ahead pitch and a reduced value of 8 kg/hp for the reverse pitch when the water flows over the hub.

Estimation of thrust from power and vice versa using DNV-GL utilizes the blade diameter and the efficiency factors depending on the type, duct configuration, forward or reverse pitching and mechanical efficiency.

The detail of the formulae is shown in the Appendix.

5.3.2 Interaction effects for Azimuth Thrusters

Depending on the type and position of the azimuth thrusters, there is the possibility of interaction among them. This depends on distance in between when the flushing angle crosses a certain limit.

A thruster is not allowed to flush directly into another working thruster in its close vicinity. The angle by which it is limited in the capability is called forbidden zones. There can be multiple forbidden zones for a single thruster with different restricting angles depending on the flushing angle limits. A DP calculation taking azimuth thruster interaction effects into account must recognize and integrate this limitation. This allows for a configuration that realistically resembles actual operations.

Forbidden zones also count in case of the thrusters in close quarters of one or multiple skegs or gondolas, if present at the aft of the hull. The thruster is not allowed to flush above baseline towards the skeg within a certain range of angle.

Flushing of dead or idle thrusters is allowed as per DNV-GL DP criteria but the effectivity is considered to be linearly reduced from the edge of the flushing angle which is maximum when the azimuth thruster is directly blowing onto the reference thruster.

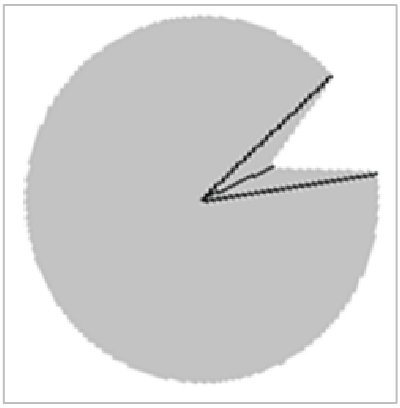

Fig. 29: Thrust loss for when flushing an idle thruster (DNV-GL)

It is not possible to describe or take into account fully the interaction effects within the scope of the present work. The developed DP tool uses the position and hull parameters to estimate the flushing and the forbidden zones. It is at the discretion of user at the end to include the restriction in the DP estimation process.

5.5 Propeller and Rudder

5.5.1 Description

The propeller and rudder combination are in affect conventional drives run through engine, gearbox and shafting. In addition to the forward or reverse thrust from the rotation of the propellers, side forces are generated by changing the steering angle of rudder behind the flow of the propeller. Placed at the aft of the vessel propellers may be aided by nozzle configurations. The propellers themselves are available in fixed pitch or variable pitch mechanisms.

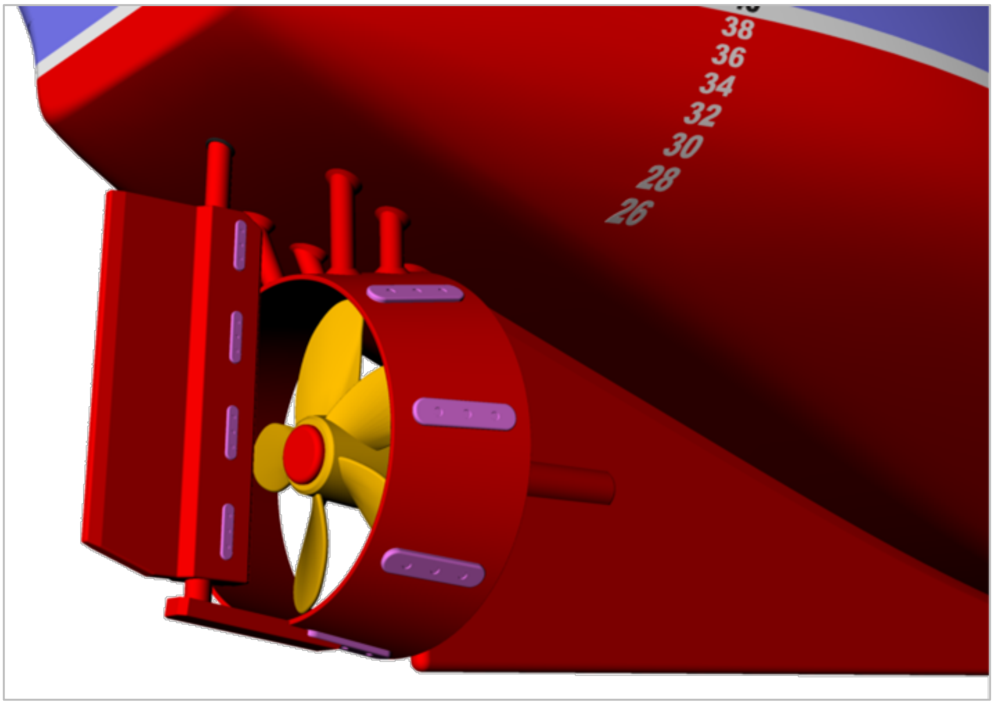

Fig. 30: Fixed pitch ducted propeller with a supported rudder at the stern

Propeller type, diameter, pitch, number of blades, rpm etc. are optimized to the hull form, desired speed, driving machinery and vibration frequencies of the vessel. In DP capability, only the parameter affecting the thrust is considered. So, diameter, rpm and pitch for a variable pitch propeller are required to deduce the nominal thrust from the available power. In the present case, IMCA or DNV-GL suggested methods have been used to empirically deduce the generated thrust. The thrust can be considered varying with rpm, but rpm is not directly handled as a variable. The optimized thrust from static DP calculation is used to estimate the relevant power required to be delivered. The DP capability estimation tool has the ability to work with four propellers and rudders at a time.

5.5.2 Estimation of Propeller forward and reverse thrusts

Propellers have high efficiency and suffer fewer interaction problems since they are optimized to the hull form. IMCA suggests the main propellers efficiency to be 13 kg/hp at forward rotation and about 70% of it for reverse rotation. There are many parameters that need to be taken into account. As mentioned earlier, propeller's direction of rotation, single or double screw, rpm, pitch for variable pitch propellers, diameter, placement with a nozzle etc. affect the power-thrust ratio. The thrust is assumed to be varying proportionally to the square of the rpm and a pitch to the power 1.7.

DNV-GL describes the efficiency values for propellers working in fixed or variable pitch, forward or reverse, nozzled or free-running for calculating the thrust and vice-versa. Moreover, it accounts for the inline losses, cross flow losses, fouling, anodes and ice interaction by a constant thrust loss of 10%.

5.5.3 Rudder

There is a wide variety of rudders to choose from for being used in the calculation process. The main input data for the rudders are therefore the type, blade area, height, maximum operating angle on each side etc.

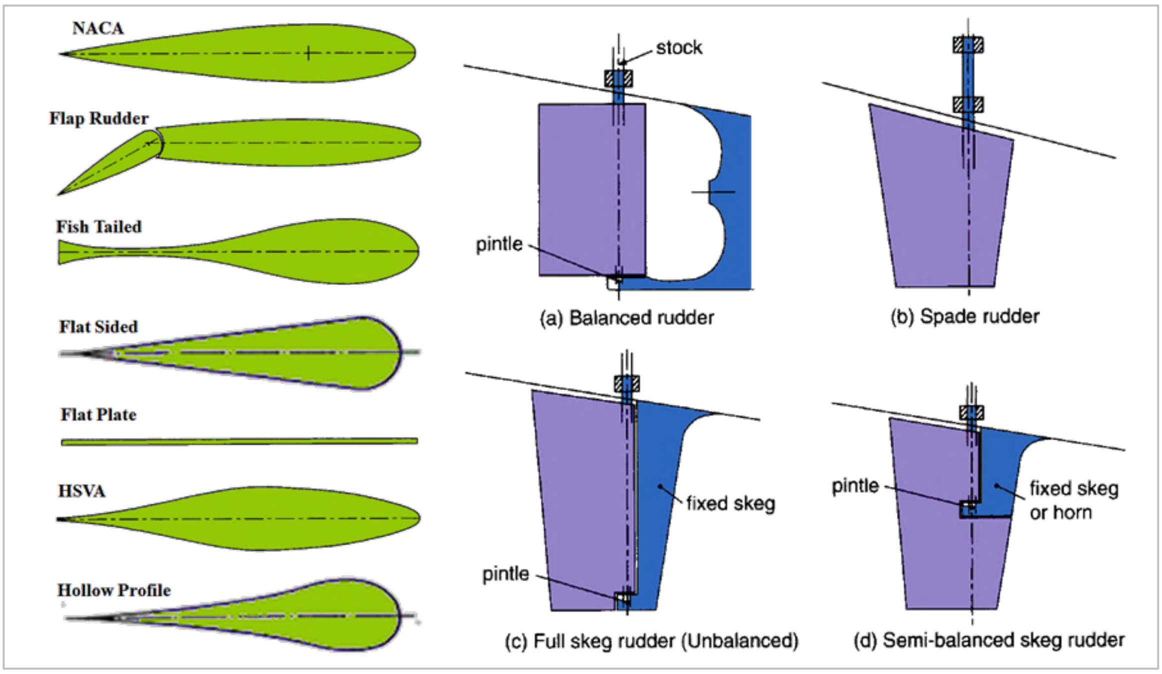

Fig. 31: Various rudder cross-section profiles (left) and arrangement types (right) [source: Marine Rudders and Control Surfaces (Turnock 2007)]

The estimation of sway force due to the lift generated at the rudder is dependent on the flow produced by the corresponding propeller. With the increase in the rudder deflection for a corresponding thrust generated at the propeller, more side force, as well as more drag, is developed at the thrust. The optimization tool must also take into account this details in estimating the balancing force and moments.

5.5.4 Estimation of Rudder forces

Rudder forces, as described in the background study, can be estimated using different empirical and theoretical formulations. The calculation methods depend on the type of the rudder profiles. The main parameters required for the estimation are the propeller diameter and thrust, the longitudinal and transverse position of the rudders, rudder area, height and aspect ratio. The propeller thrust is responsible for the induced flow at the rudder.

Table 9: Different types of rudders and their force calculation methods in the DP tool

Sl.	Profile	Method of Calculation
1	Supplied / Manual Data	Empirical
2	NACA	Theoretical
3	NACA	DNV-GL
4	Becker Flap	Empirical
5	Spade Rudder	Empirical
6	Hollow Profile	DNV-GL
7	Flat-Sided	DNV-GL
8	Fish Tail	DNV-GL
9	Flap	DNV-GL
10	Behind Nozzle	DNV-GL
11	HSVA	DNV-GL

The lift and drag coefficients depend on the aspect ratio and the steering angle of the rudders from the mean position. The amount of lift and drag is also affected if the rudder is behind a fixed nozzle propeller. The parameters are used to generate lift and drag coefficients which are further used with the rudder area and deflection to calculate the forces. Other data can be obtained from the suppliers themselves like in the following figure:

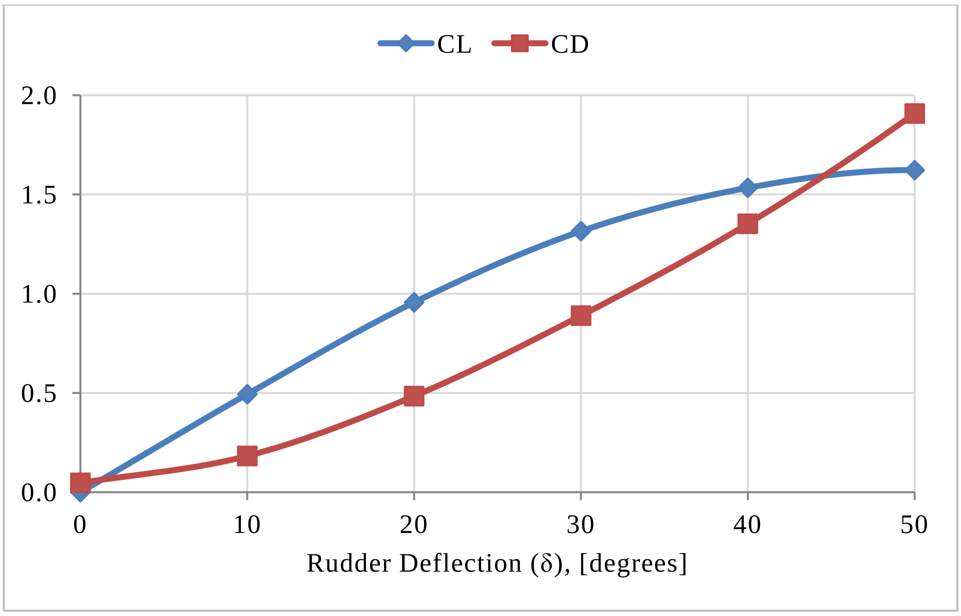

Fig. 32: Variation of lift coefficient (CL) and drag coefficient (CD) with increase in rudder deflection for Becker Flap rudder

6. DP CAPABILITY ESTIMATION

In the following chapter, the DP capability calculation is done using the developed DP tool for an example vessel. The external forces acting on the vessel due to wind, current and wave are calculated first based on the profile and particulars of the vessel. Then, various stages of the calculation like static balance, thruster optimization, DP optimization is performed and presented.

The calculation is followed by the creation of DP polar as well as other comprehensive plots. All the DP estimation process goes through a similar calculation procedure as was defined in the methodology in chapter-3.

6.1 Estimation of Environmental Forces

6.1.1 Wind Forces

The following figure shows the profile of multipurpose vessel with underwater area represented in red and the above water region in blue. Only the blue portion is of concern when calculating the wind loads.

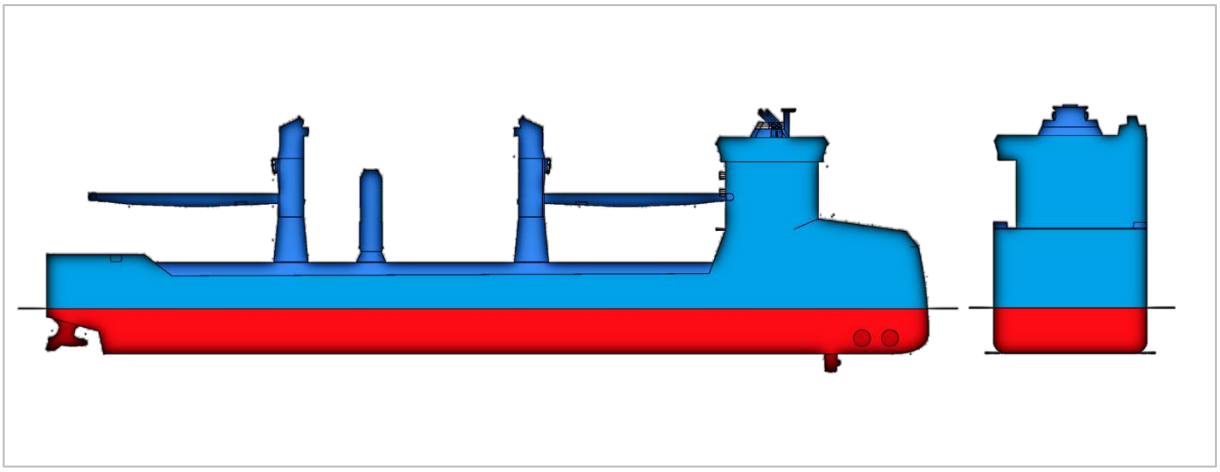

Fig. 33: Frontal and lateral projected area of the vessel

The basic parameters of the vessel are given in the table on the following page.

Table 10: Basic parameters for the calculation of wind forces

Vessel Type	**Multipurpose Vessel**
Frontal Projected Area (A_F)	716 m^2
Lateral Projected Area (A_L)	1841 m^2
Long. Center of Later Area (Xw)	77.75 m from AP
Wind Velocity (Vw)	10 m/s
Direction (ϴw)	30 deg.

For a multipurpose vessel with the above data sets, the obtained coefficients and respective wind loads calculated with applicable methods give:

Table 11: Estimation of the wind surge, sway and yaw coefficients and corresponding loads

Methods	**Cwx**	**Cwy**	**Cwn**	**Fwx [kN]**	**Fwy [kN]**	**Mwz [kN]**
IMCA	-0.97	-0.40	-0.078	-42.90	-45.83	-1246.9
Blendermann	-0.95	-0.43	-0.07	-41.81	-48.84	-1138.1
Isherwood	-1.02	-0.29	-0.03	-44.84	-32.32	-513.7
DNV-GL	-0.61	-0.45	-0.11	-26.70	-50.95	-1789.3
Gould	-0.57	-0.51	-0.08	-25.03	-57.3	-1313.7

It is seen that for a single wind speed and direction each of the related methods gives varying results, though the range is similar. This is why it is suggested to mention the method used in the estimation of loads.

6.1.3 Current

At the preliminary design stage, although the hull shape during the DP capability calculation is available, it is very rudimentary. Only the basic features are therefore used to estimate the current load on the underwater hull.

Table 12: Basic hull parameters for the calculation of current loads

Vessel Type	**Multipurpose Vessel**
Length between pp. (L_{BP})	142.1 m
Breadth moulded (B_{MLD})	25 m
Design Draft (T)	7.2 m
Transverse Underwater Projected Area (A_{UT})	220.26 m^2
Longitudinal underwater Projected Area (A_{UL})	1841 m^2
Current Velocity (Vc)	0.5144 m/s [1 knot]
Direction (ϴc)	30 deg.

For the multipurpose vessel with the above-related particulars, the corresponding coefficients and loads at the IMCA-140 recommended current speed of 1 knots gives the results given below. The direction of incidence is taken to be same as that of the wind used in the previous section.

Table 13: Estimation of current surge, sway and yaw coefficients and corresponding loads

Methods	Cwvx	Cwvy	Cwvn	Fwvx [kN]	Fwvy [kN]	Mwvz [kN]
IMCA(Nienhuis)	-0.017	-0.353	-0.090	-0.42	-49.04	-1769.8
DNV-GL	-0.061	-0.3	-0.077	-1.48	-41.62	-1526.7

6.1.5 Wave

The estimation of the wave loads takes two steps. In the first step, the wave height, corresponding crossing period, and wave encountering frequency is estimated from the available data. This comes from the wind-driven wave data matching with either IMCA suggested North-Sea Correlation or from DNV-GL suggested World-wide Scatter Diagram. For a wind speed of 10m/s, the methods generate the following results:

Table 14: Estimation of significant wave height, wave peak and crossing period, and encountering frequency for a wind speed of 10 m/s

Methods	Hs [m]	Tp [s]	Tz [s]	**ω** [rad/s]
North Sea Correlation (IMCA recommendation)	3.21	8.41	6.57	0.96
World Wide Scatter Diagram (DNV-GL recommendation)	1.90	7.25	5.16	1.22

In the second step, it is necessary to calculate the second order wave drift loads. The waves are considered to be coming from the same direction as that of the wind. DNV-GL gives the following wave loads and moment on the vessel and uses the values from world-wide scatter diagram.

Table 15: Estimation of wave loads for the multipurpose vessel at wind speed of 10 m/s

Method	Fwvx [kN]	Fwvy [kN]	Mwvz [kN.m]
DNV-GL	-15.85	-82.4	-407.2

6.3 Thrust Calculations

6.3.1 Estimation of DP Thruster scenario

It is possible to determine the thrust configuration of the propulsion system for the ambient forces and defined position and power ranges. The variables are the power and working angles of the thrusters. The wind velocity determines the wind and wind-driven wave loads. The current velocity on the hull gives the current load. The constraints are the number, type and position of the thrusters that are pre-defined. The viable power range as an initial estimate is supplied. The objective is to find optimum power and working angle of the propulsors to balance the ambient forces.

The term optimum means that the minimum power that is enough to counteract the incident loads in static balance, i.e. maintaining the position and heading. For a particular direction of the ambient forces, this balance must be attained in such a way that the thruster creates a force equal to the resolved loads in the surge and sway directions. Moreover, the combined moment in effect should also counteract the yaw moments.

For the multipurpose vessel with the wind, current and wave-induced loads calculated in the previous sections, two bow thrusters and three azimuth thrusters produce the results given in the table on the following page.

Fig. 34 represent a schematic result of the calculation showing the thrust configuration and the desired direction of the azimuth thrusters. It is important to note that the position and heading balance is obtained although it may not seem at first sight the thruster direction is opposing the incoming forces. In fact, the thrusters work within their defined capacities to reorient themselves such that their combined effect is responsible for obtaining the balance.

Table 16: Estimation of optimized thrust configuration at 10 m/s wind speed

Environmental Constraints:				
Wind Velocity (Vw)	10 m/s			
Current Velocity (Vc)	0.5144 m/s [1 knot]			
Incident angle of wind, current and wave (Θ)	30 deg.			
Thruster Constraints:				
Bow Thruster-1	Power- 2340 kW Location- 135.95m from AP			
Bow Thruster-2	Power- 2340 kW Location- 131.15m from AP			
Azimuth Thruster-1	Power- 1900 kW Location- 127.55m from AP			
Azimuth Thruster-2	Power- 5075 kW Location- 0.95m AP, 6m OCL			
Azimuth Thruster-3	Power- 5075 kW Location- 0.95m AP, -6m OCL			
Ambient Loads:				
	Selected Methods	**Fx [kN]**	**Fy [kN]**	**Mz [kN.m]**
Wind Loads	IMCA	-42.90	-45.83	-1246.88
Current Loads	IMCA	-0.42	-49.04	-1769.78
Wave Induced Loads	DNV-GL	-15.85	-82.38	-407.25
Resultant Forces:				
Surge (Fx)	-59 kN			
Sway (Fy)	-177 kN			
Yaw (Mz)	-3424 kN.m			
Optimized Thrust Configuration for Static Balance:				
	Thrust [kN]	Power [kW]	Azi. Thr. Angle [deg.]	
Bow Thruster-1	9.34	80.71	-	
Bow Thruster-2	114.57	990	-	
Azimuth Thruster-1	0	0	0	
Azimuth Thruster-2	0	0	0	
Azimuth Thruster-3	79.23	579.3	41.97	

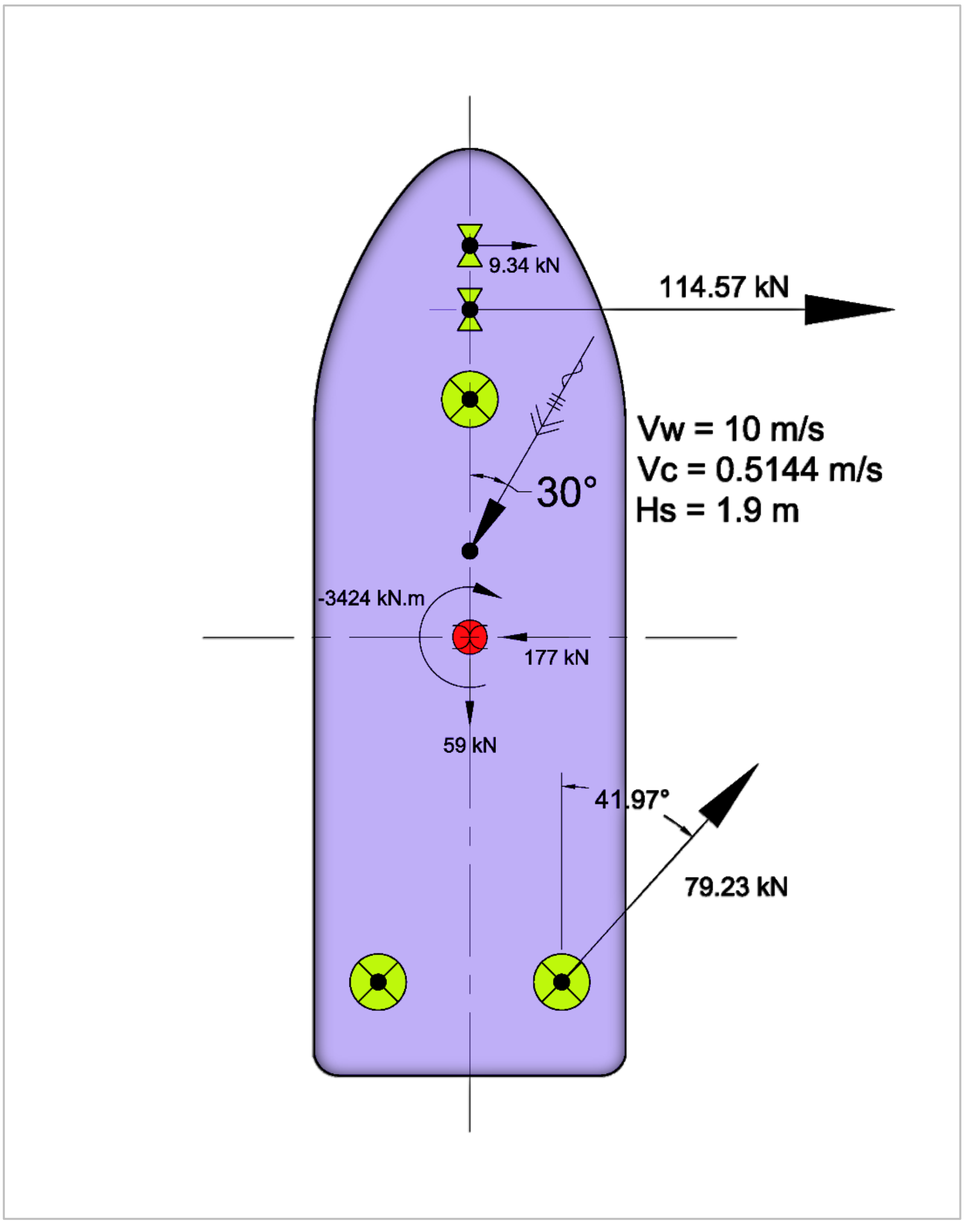

Fig. 34: Optimized thrust and direction configuration for static balance for constant wind, current speed, wave height and constant direction

6.3.2 Maximum Capability

The calculation of the maximum capability determines the highest wind speed that can be sustained using the defined thruster configurations utilizing the maximum thrust capability while maintaining the static balance. Since DP Plot is a representation of the maximum sustainable wind speed, the maximum capability calculation is of great significance. The optimization goal for the process is to maximize wind values employing maximum thruster capacity required for balancing the corresponding ambient loads. For the defined operational ranges and power, collinear wind, current and wave directions, for a fixed current speed, variable wind with variable wind-driven waves are the contributing parameters for the calculation of the ambient loads on the vessel.

With the multipurpose vessel, for instance, and following input and thrust parameters and operational limits, static balance and optimization produce the 30.8 m/s as the maximum attainable wind coming at an angle of 30 degrees. The final thrust distribution is also presented in the table below:

Table 17: Calculation of the maximum capability for the vessel with available thrusters

Calculated Maximum Capability:				
Calculated Max. Sustainable Wind Velocity (Vw)		30.08 m/s		
Constant Current Velocity (Vc)		0.5144 m/s [1 knot]		
Wave Height at max. wind (Hs)		10.5 m		
Incident angle of wind, current and wave (Θ)		30 deg.		
Reserve power allowance		25%		
Ambient Loads at Max. Wind:				
	Selected Methods	**Surge, Fx [kN]**	**Sway, Fy [kN]**	**Yaw, Mz [kN.m]**
Wind Loads	IMCA	-388.14	-414.67	-11280.85
Current Loads	IMCA	-0.42	-49.04	-1769.78
Wave Induced Loads	DNV-GL	-199.19	-811.14	-4009.71
Resultant Loads:		-588	-1275	-17060
Table 17 (contd.):				

Optimized Thrust Configuration for Static Balance:				
	Thrust [kN]	Azi. Thr. Angle [deg.]	Power [kW]	Capacity Utilization [%]
Bow Thruster-1	271	-	1872	80
Bow Thruster-2	271	-	1872	80
Azimuth Thruster-1	260	94.15	1520	80
Azimuth Thruster-2	447.2	0	2639	52
Azimuth Thruster-3	499	71.5	2918	57.5

6.4 DP Capability Calculation

The main objective of the DP Capability Calculation is to obtain the DP Plot. The maximum capability calculation done above for a particular wind, current and wave direction, defined current velocity, is repeated for 0~360 degrees range at 5 degrees increments. 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. Such an optimizing calculation usually takes around 20 mins. to perform in Excel environment. DP Plots are obtained by interpolating the maximum wind speeds corresponding to the direction. Thrust Plots are obtained by the interpolation of vector summation of all thrusts corresponding each direction. The tabulated result of the calculation for the multipurpose vessel is shown in the Appendix.

6.4.1 DP Plot

The representation of the DP Plot follows IMCA-140 guidelines as discussed previously. Other calculation information is also presented so that only this page is enough to represent the DP Capability of the vessel.

DP Capability Plot

Project: Multipurpose Vessel **Rev.** 0

Main Particulars			
Length betw een perpendiculars	:	**142.1**	[m]
Loaded Waterline Length	:	**145.0**	[m]
Breadth moulded	:	**25.0**	[m]
Draught	:	**7.2**	[m]
Block coefficient	:	**0.835**	[---]
Displacement	:	**21902**	[tonnes]

Calculation Parameters			
Maximum Wind Speed	:	**50.0** [m/s]	(97.2 Knots)
Current Speed (fixed)	:	**0.51** [m/s]	(1Knots)
Wave Height	:	**Wind Dependant**	
Wind Load Estimation	:	**IMCA**	
Current Load Estimation	:	**IMCA**	
Wave-Drift Estimation	:	**DNV-GL**	

Thruster	Thrust [kN] (+ve=Fwd)			P [kW]	[%]
TT No. 1	-271	to	271	2340	80%
TT No. 2	-271	to	271	2340	80%
AT No. 1	-160	to	260	1900	80%
AT No. 2	-427	to	694	5075	80%
AT No. 3	-427	to	694	5075	80%

Other Considerations		
Wind Incedent Angle	:	**0 ~360** [deg]
Wave & Current	:	**Collinear with Wind**
Dynamic Allow ance	:	**25.0** %
Interaction Effects	:	**Not Included**
Additional Forces	:	**Not Included**

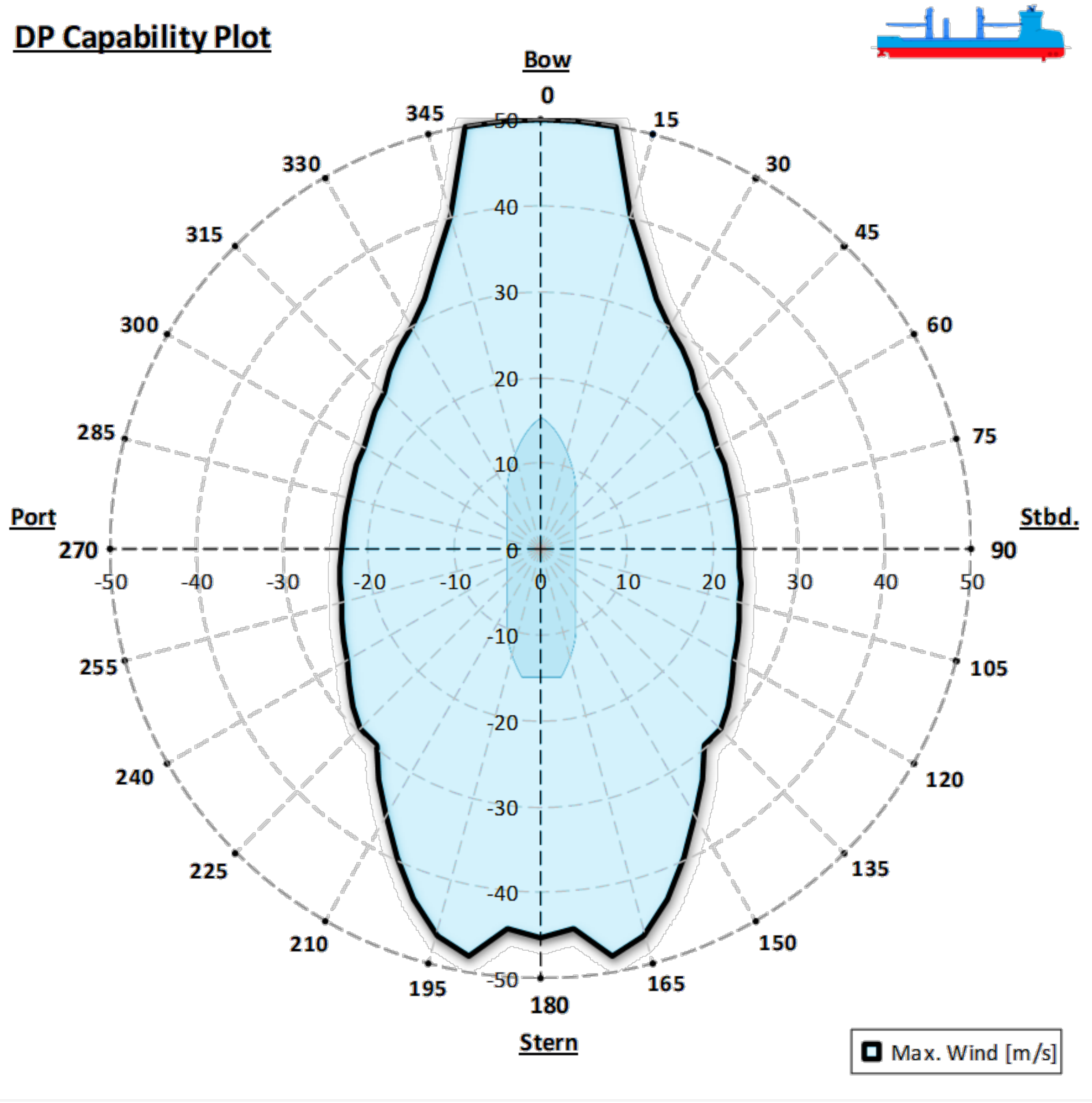

Fig. 35: DP capability plot for the multipurpose vessel

6.4.2 Failure Plot

Failure Plot construction is similar to the DP Plot except that the most effective thruster or combination of the thrusters in the power line fail and do not contribute to the DP static balance. Due to the reduced directional thrust capacities, the maximum wind that can be sustained is reduced. The norm is to represent the failure plot in the DP polar plot to compare the difference. In the present case, all the factors related to the generation and supply of electrical power and their failure modes are ignored and only the failure characteristics are studied.

For the considered multipurpose vessel, if the switchboard-power train that controls Bow Thruster-2 and Port Azimuth Thruster-3 fail we get the failure weather envelope as shown in the figure below.

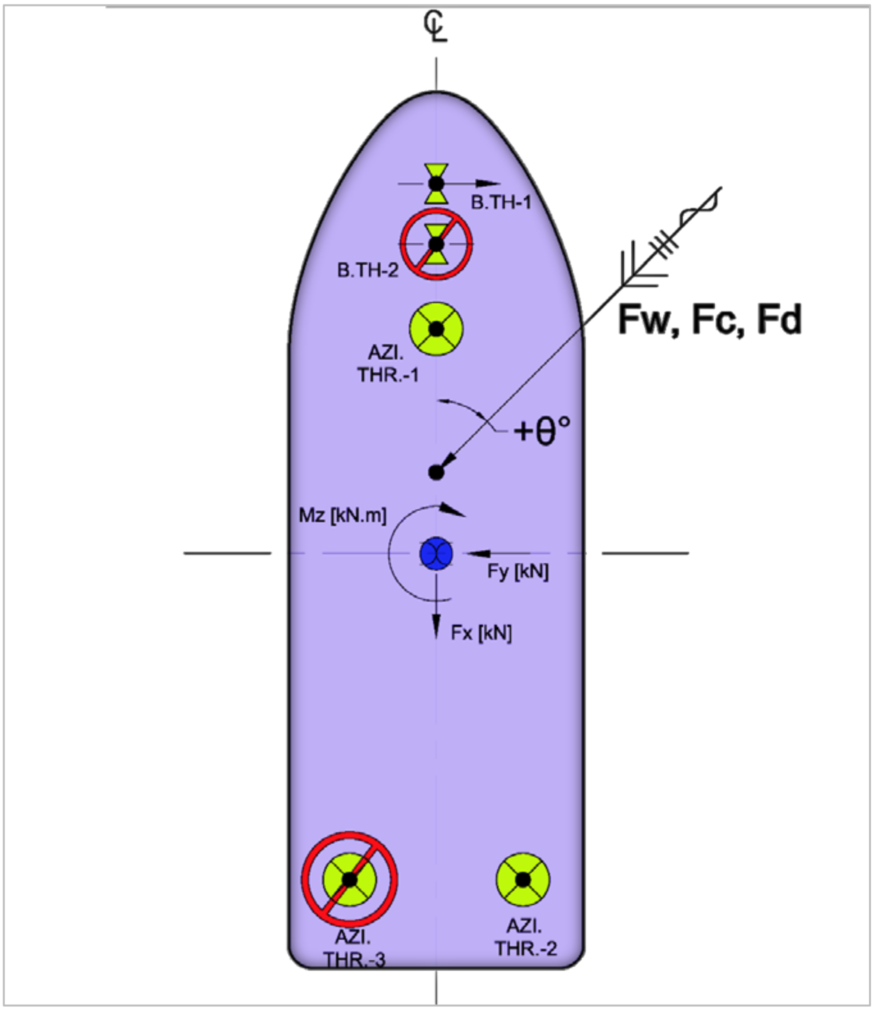

Fig. 36: Failure of Bow Thruster-2 and Azimuth Thruster-3 as an example of possible failure

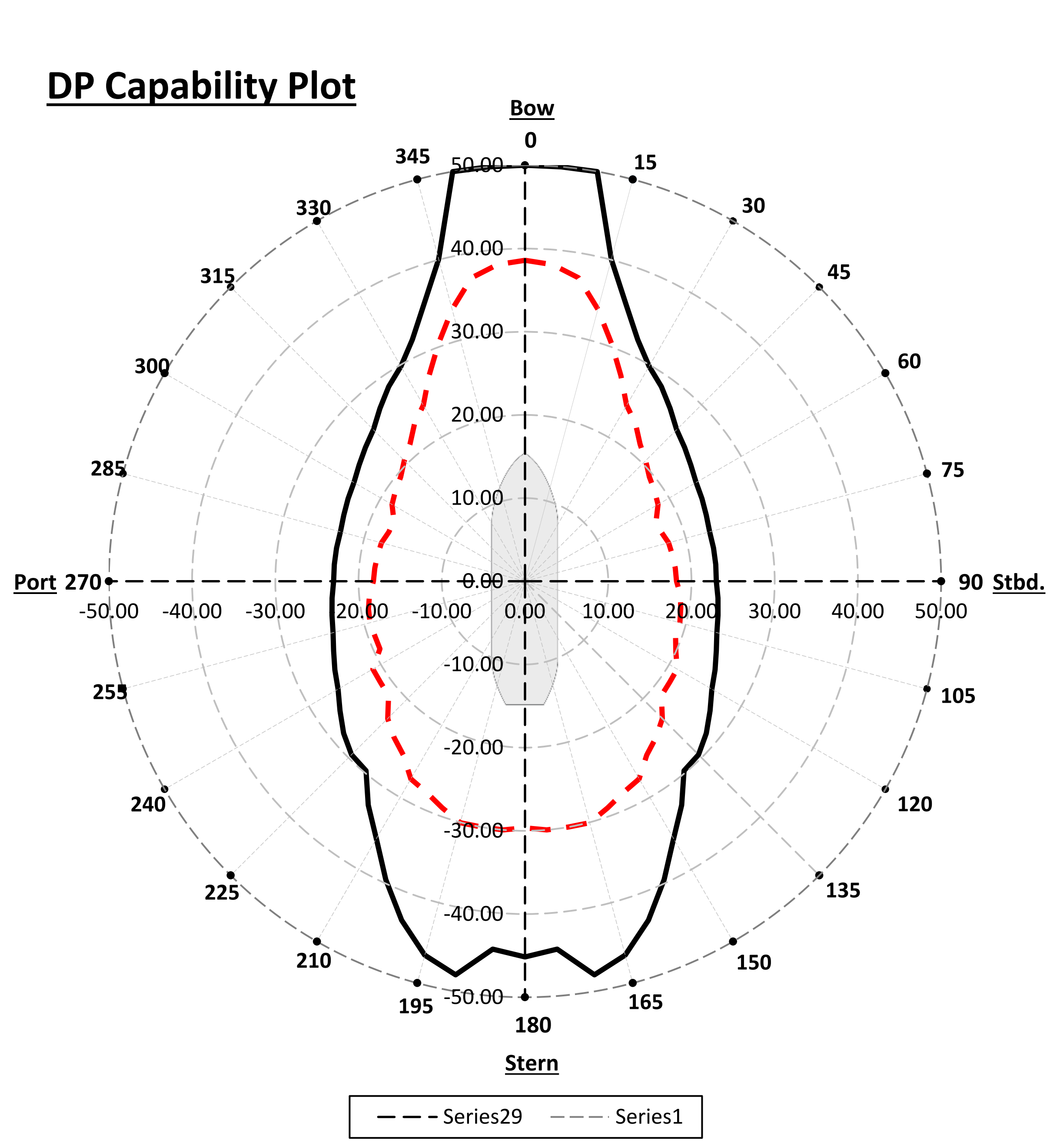

Fig. 37: DP plot showing the full DP capability and the reduced capacity after considered failure

6.4.3 Thrust Plot

The addition of the thruster in the optimized configuration at full power and interpolating between the angles gives the thrust plot. The thrust plot for the multipurpose vessel gives the result shown on the following page.

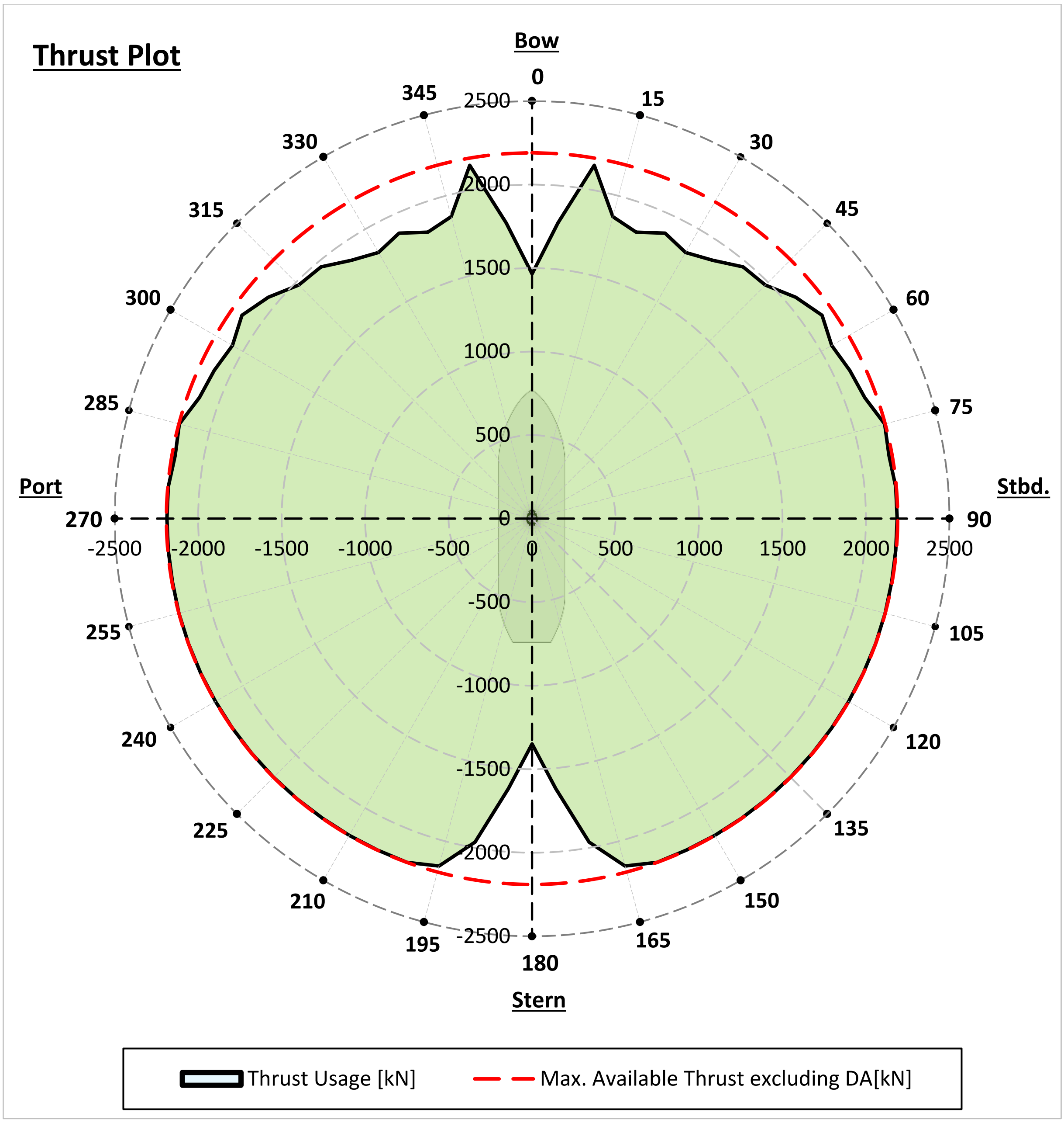

Fig. 38: Thrust polar plot at full DP capability

The plot shows that the optimized thrust requirements vary with the angle. Thrusters are used to their full capacity near the beam load conditions. With wind, current and waves coming from head or aft, the plot shows that the loads can be dealt with less power usage from the thrusters and the rest of the thrust to the full capacity, remains as a reserve. It is also to note that the Max. Available Thrust shown in red dashed-line is excluding the Dynamic Allowance, which means that total directional thrust considering the reserve reaches up to 2740 [kN].

6.4.4 *Other Comprehensive Plots*

These plots represent in details the variation of the thrust configuration with the increment of incident angles of the incoming forces. These plots are directly obtained from the DP capability analysis. The calculation starts with the wind, current and wave coming directly at the vessel's bow, and with the change in this angle clockwise, the static calculation produces the thruster output requirements for balancing the external forces.

In the graph of linear thrust utilization plot, the thruster output is seen to vary and the overall usage for each thruster with respect to its maximum capacity can be analyzed. The calculation results show that static balance can use up to a maximum of 80% of its available power. The rest is being reserved for the dynamic variation of the ambient seaway. The main significance of this plot is to visualize whether the allotted thrust capacity is enough to support the DP vessel and whether they are over or under-utilized. The plot below represents the variation from 0 to 180 degrees. The variation for 180 to 360 degrees is just the mirrored output about the 180-degree vertical gridline.

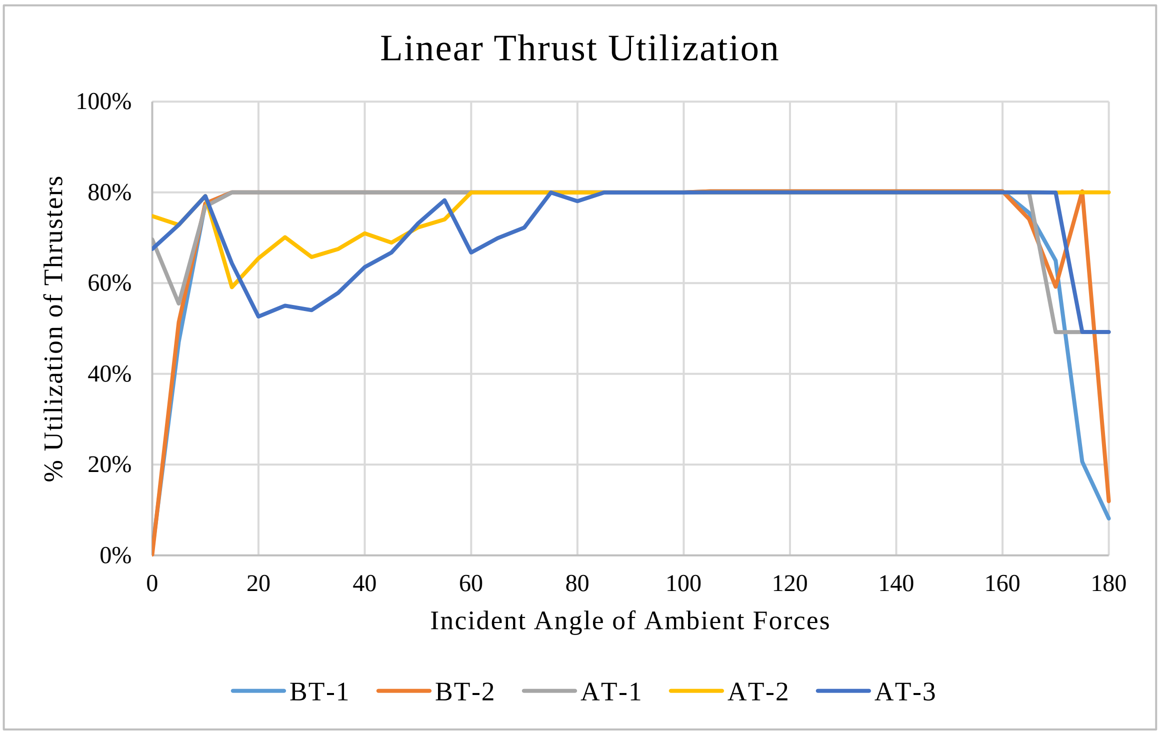

Fig. 39: Utilization of thruster with the variation of ambient force directions

The following plot represents the variation of the angles of the azimuth thrusters and shows how the thrusters with the directional flexibility adapt to the change of direction of the incoming forces for obtaining the static balance. As an example, for the external forces incident at 40 degrees to the vessel, each of the thrusters has its own alignment suitable to negotiate the force as well as the moment balance. Since the interaction effect for the thruster in this calculation has been neglected, there are not barred, forbidden or flushing zones seen in the plot.

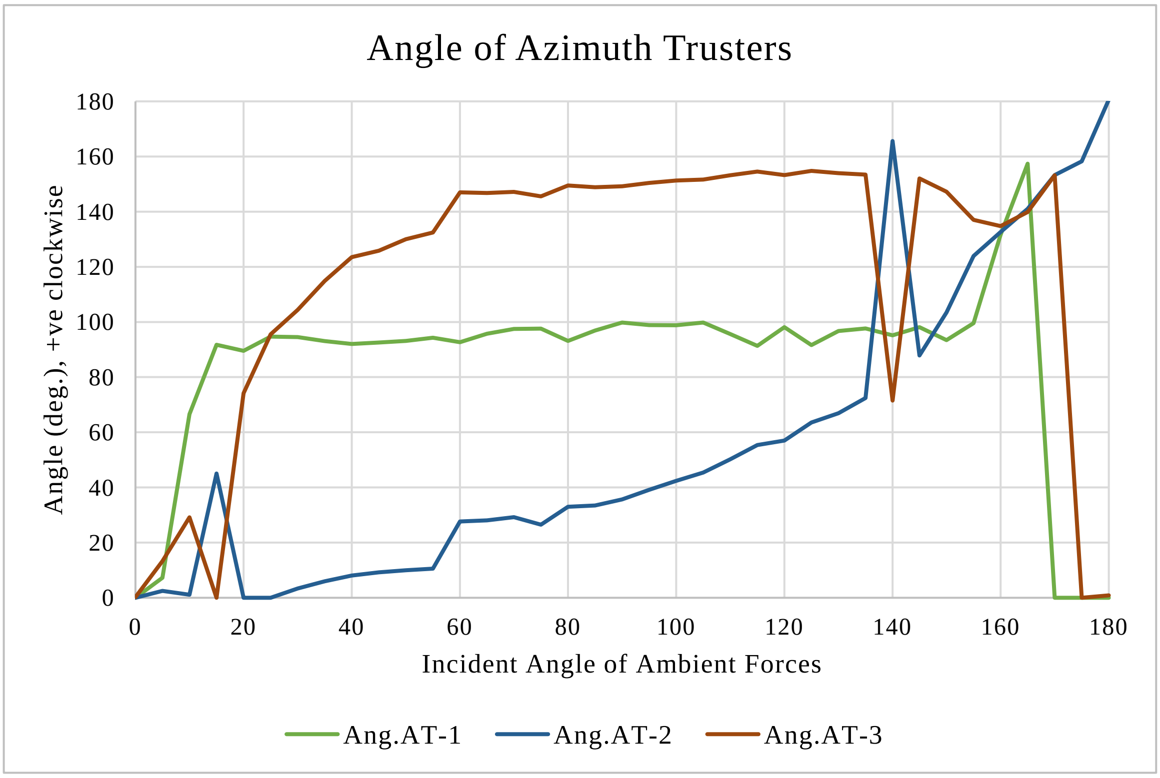

Fig. 40: Variation of the thruster allignment with the change in the direction of the external forces

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7. VALIDATION

In the validation part, the accuracy and reliability of the excel DP capability tool are tested. The optimization of thrust values, considered as the backbone of the static DP estimation, is verified against standard commercial optimization program ModeFrontier to check the convergence as well as the precision of the results.

The DP plot, which is the representation of the overall DP estimation, is compared in the second part with multipurpose vessel, tanker and cruise vessel of known DP configuration. An account of the similarity and the differences with possible underlying factors are discussed in the following subsections.

7.1 Validation of the thruster optimization macro using Genetic Algorithm in ModeFrontier

The thruster scenario estimation for the multipurpose vessel mentioned in the previous chapter is put to test by setting the propulsion parameters as variables and static balance as the objective function.

The main variables of the 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 ambient forces are considered corresponding to a wind velocity of 30 m/s, constant current of 1 knots and wave depending on the wind.

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 same procedure was previously adopted in the excel based modified solver to determine the thruster configurations. This time, in ModeFrontier, with a set of the initial generation of the onset values, the optimization is done by using genetic algorithm. Each of the surge, sway and yaw balance are set as the objective function of the problem.

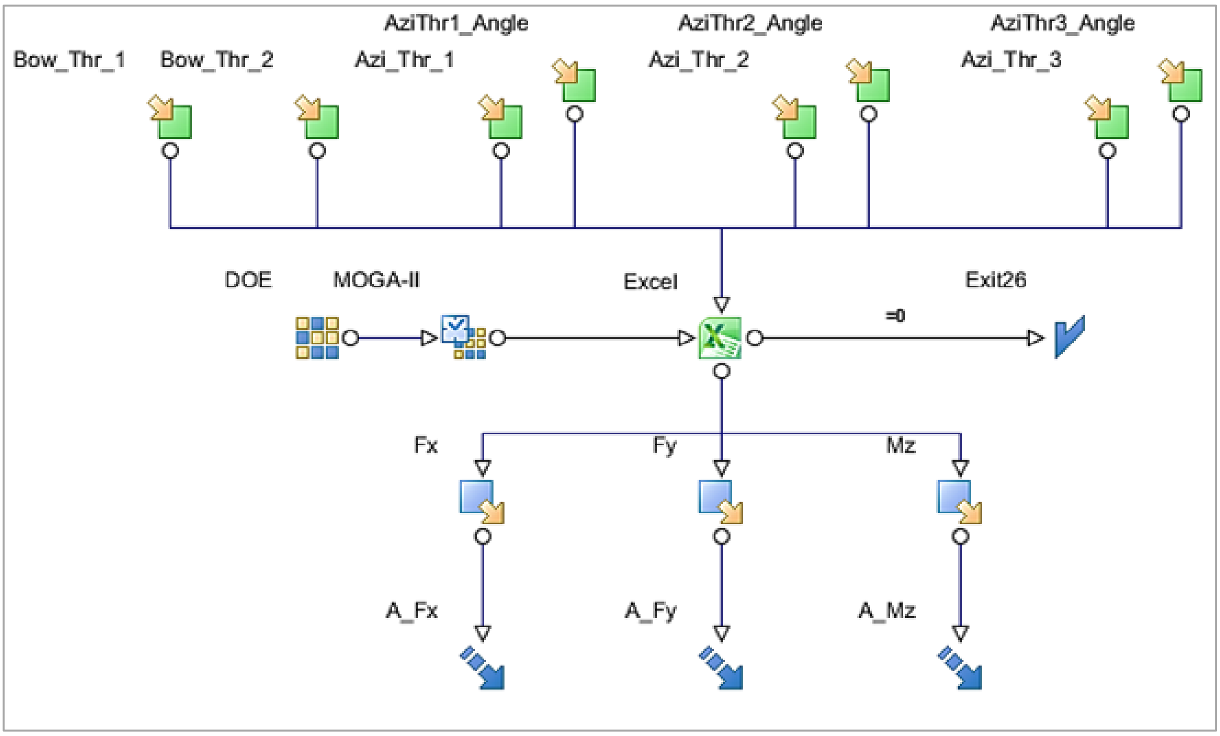

Fig. 41: Workflow chart for MOGA optimization for DP thruster scenario

The run with 1100 generations cycle is tested for convergence to a global optimal solution with the help of convergence graphs and Pareto frontier. The following graph shows the variation of the results for each objective function across generations as the search continues for the desired balance.

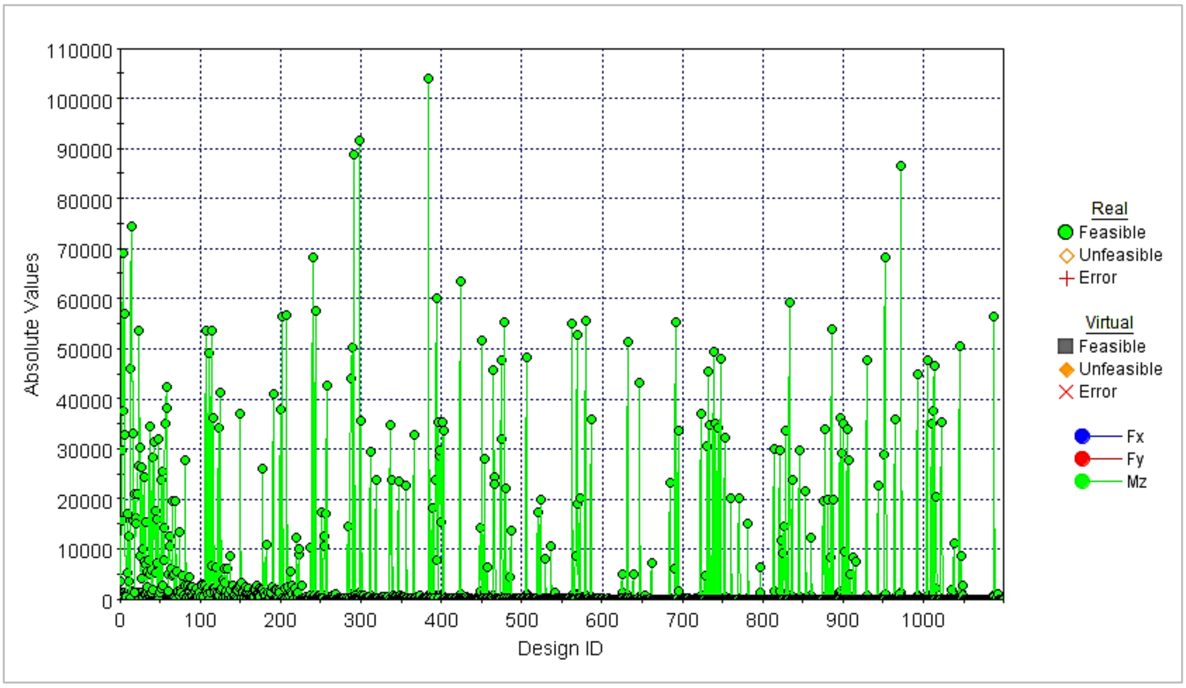

Fig. 42: Real and feasible solutions for the surge, sway and yaw thrust balance

The Pareto frontier shows the solution domain of the sum of the incoming forces and the applied thrust. With each generation of variables containing thrust and angle parameters of the vessel, three solutions for the surge, sway and yaw values are obtained. The nearer the sum is towards the zero point, the better is the balance of thrust and external forces as there should not be any force or moment residue at perfect balance.

The real and feasible solutions scramble with the initial values and are further away from the objective mark. With the increase in generations, the points get closer and closer to zero and thus most of the points at the latter stage is seen to accumulate near the origin as can be seen in the graph below.

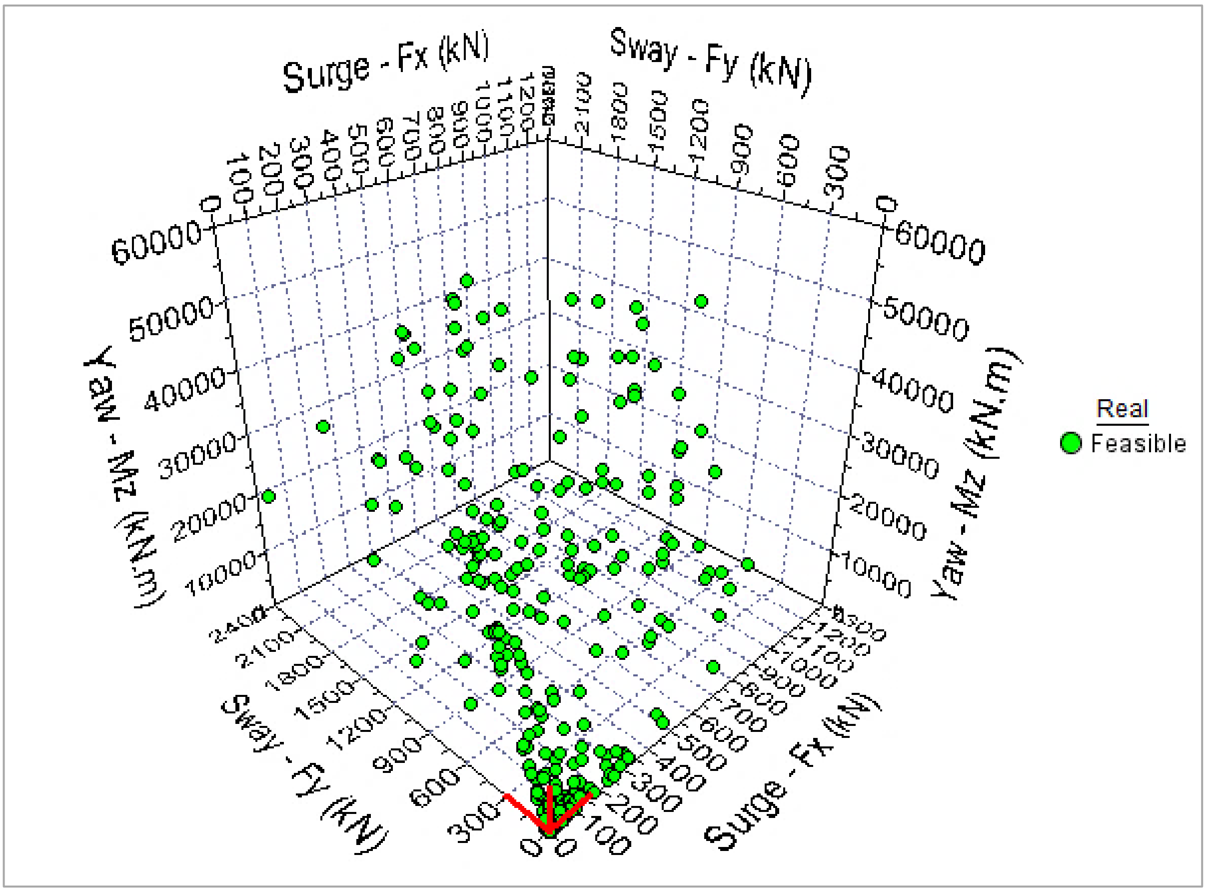

Fig. 43: Convergence to global optimal balance represented by Pareto frontier concentrating at zero value after 1100 runs

The final parameters obtained from the process are matched with the excel solver results to confirm the reliability of the excel optimization process. The excel results for thrust and azimuth angles shows good agreement with the ModeFrontier values.

Table 18: Optimized Thrust Solver Comparison for Vw 30m/s

	Thrust Values [kN]			Azimuth Thruster Angles [deg]		
	Excel Solver	ModeFrontier MOGA	Difference [%]	Excel Solver	ModeFrontier MOGA	Difference [%]
Bow Thruster-1	271	271	0	-	-	-
Bow Thruster-2	271	271	0	-	-	-
Azimuth Thruster-1	260	260	0	85.7	86.7	1.15
Azimuth Thruster-2	429	423.6	1.28	0	0	0
Azimuth Thruster-3	493.2	494.9	0.34	73.6	72.64	1.30

Most of the values are equal in both cases with maximum difference less than 1.5%. Considering the rate of convergence, excel solver rapidly converge within 20~30 seconds while the total 1100 runs for MOGA take more than 2.5 hrs. This difference is mainly due to the fact that optimal search across multiple generations containing genetic variants takes longer time for global convergence in MOGA.

The results, therefore, confirm that the tool can be used as an optimization tool for the process with some added advantages in terms of time, accuracy and flexibility of use.

7.2 Validation of DP capability with reference ships

In the following subsections, DP plots for the multipurpose vessel, a tanker and a cruise vessel obtained from the excel DP tool is matched with the available DP data. The chosen vessels are 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 excel 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.

In each case, the type of the vessels, operational characteristics, thruster types and constraints, position and the ambient conditions are different. The main objective of choosing the vessels in the validation process is based on this fact they have the mentioned wide differences among them. Therefore, a DP tool that has the capacity to estimate successfully the results for each of them will also be suitable for other vessels with intermediate features and can be used with a certain degree of confidence.

7.2.1 Multipurpose vessel

The DP estimation for the multipurpose vessel is already done in the previous chapter. The graph on the following page is obtained when excel DP plot is compared with the available results from reference data.

In the graph, the reference line-1 comes from commercially obtained DP capability estimation for the vessel and reference line-2 comes from web-based DP optimization program from DNV-GL. In all the cases, the vessel avails two bow thrusters and three azimuth thrusters. The capacity and range of the thrusters are kept same. Excel and Ref-1 use wind coefficients from Blendermann, current velocity of 1 knots and wave correlation data from the North Sea.

The DNV-GL method represented by the line Ref-2 uses their own empirical formula for wind coefficients, own current speeds according to the wind velocities defined in the table shown in Appendix-A6, wind correlation data from world-wide scatter diagram and wave load using their own empirical relations.

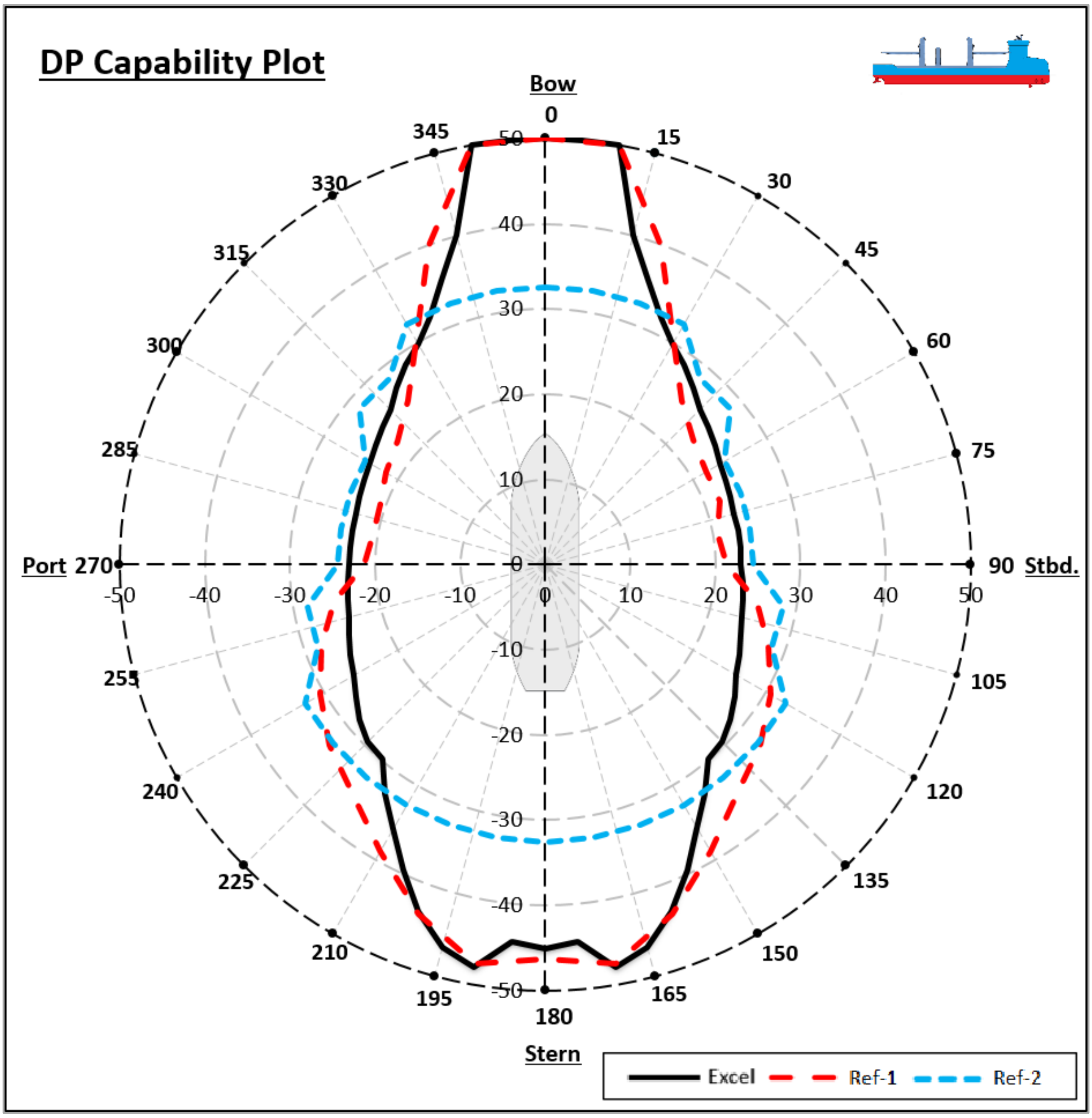

Fig. 44: Comparison of the DP capability plot obtained from excel tool with the references

The excel optimized DP plot is seen to closely resemble the reference lines. The difference with the Ref-2 line is due to the practical wind speed limitations imposed in the DNV-GL calculation as they consider wind speed of 32.6 m/s as the upper ceiling of the DP estimation. The excel tool and Ref-1 follow the IMCA recommendation of 50 m/s for Vmax.

7.2.2 Tanker

The tanker being considered has two bow thrusters, two stern thruster and two controllable pitch propellers with flap rudders. There are no azimuth thrusters in the vessel. The stern thrusters are placed in skegs at each side. The figure below shows the projected longitudinal and transverse profile of the vessel to the incoming wind, current and waves.

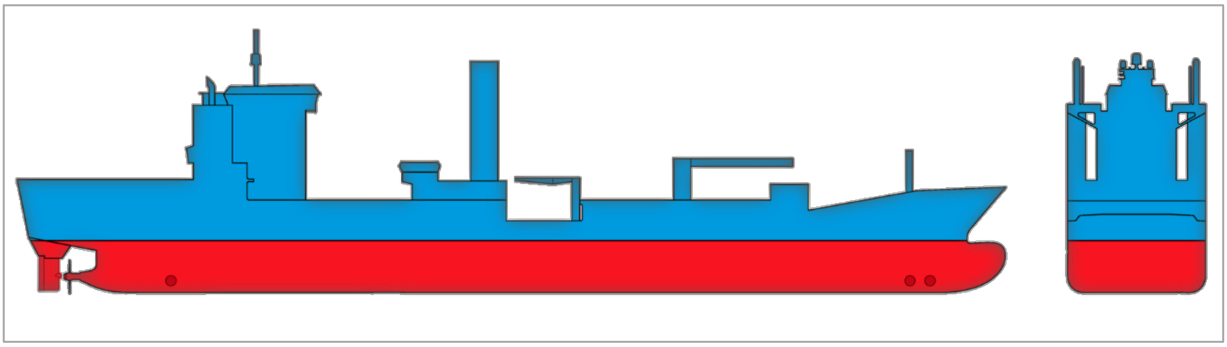

Fig. 45: Frontal and lateral projected area for the Tanker to wind, current and waves

The power constraints for the bow and stern thrusters are 800 kW and 400 kW respectively. The bow thruster is considered to be acting with same effectiveness on both sides but the stern thrusters are considered only able to wash outwards (as blowing inward into the hull and towards another stern thruster will have significant interaction effects). The propellers with a diameter of 5.2m have forward thrust capacity of 1000 kN and 80% of it in reverse.

The optimization for the DP capability for both the excel tool and the reference take into account wind load estimated from Blendermann, IMCA current load at 1 knots, and wave load corresponding to a restricted wave height of 2.5m.

The plots on the following page show that the excel DP plot follows the trend of the reference throughout. However, it shows a reduced capacity for all angles of the incoming forces. Nevertheless, the values closely match throughout except in some particular regions. The representation can be considered more conservative with respect to the reference.

Transverse thrusters are considered the weakest in terms of capacities. Near the 90 and 270 degree regions, the incoming external forces are coming only from the beam, so, only thrusters providing sway forces should remain most active. The conventional propeller and rudder arrangement are not the primary thrusting medium to negotiate forces from these angles. The reference plot shows an abrupt peak touching 30 m/s mark for wind speed. Considering the discussed limitations and capability of the thrusters themselves, it is not practical that only thrusters are able to rear so much power to station keep the vessel at 30 m/s of beam wind conditions. That is why, near the 90 and 270-degree regions, the interpolation for the excel values are more logical than the reference.

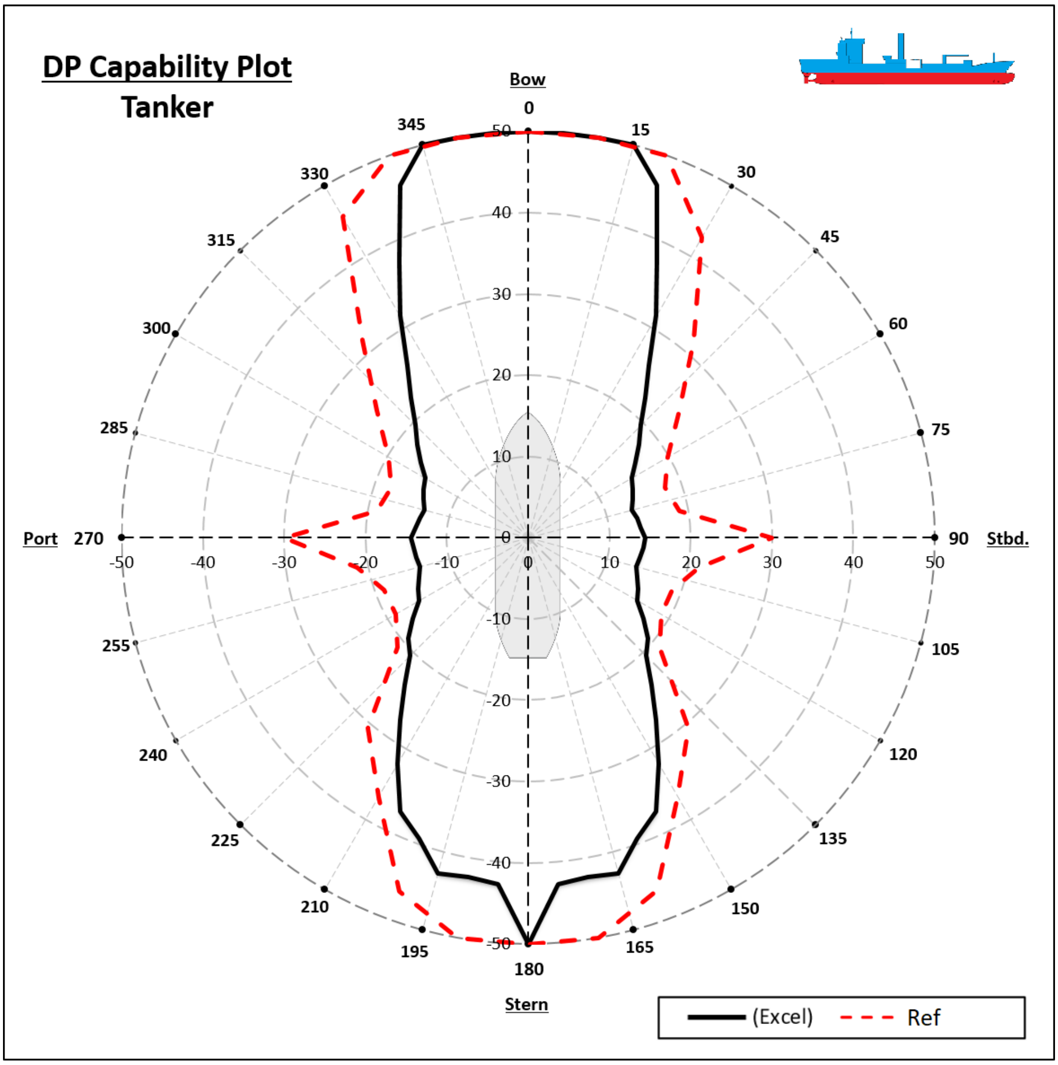

Fig. 46: Comparison of the DP capability plot obtained from excel DP tool with the reference

7.2.3 Cruise Vessel

Cruise vessels use DP for virtual anchoring in pristine areas. Near the shore areas, the main consideration is the load due to its huge projected area to the prevailing wind, and effect of current and waves are secondary. The vessel in analysis requires its DP capability to be defined on its wind sustainability only.

The vessel is equipped with two bow thrusters of 2700 kW each, one stern thruster of 1500 kW, and two shaft-driven controllable pitch propellers with flap rudders. The capacity of all the transverse thrusters in forward and reverse direction is same. Each of the 5-meter propellers at full forward thrust generates 800kN of force and 640kN at back gear.

Fig. 47: Frontal and lateral projected area of the Cruise Vessel to the wind, current and waves

Due to the profile of the vessel, a variation of the wind coefficients with a change in direction is different from other vessels. The surge, sway and yaw coefficients are supplied from experience with similar vessels.

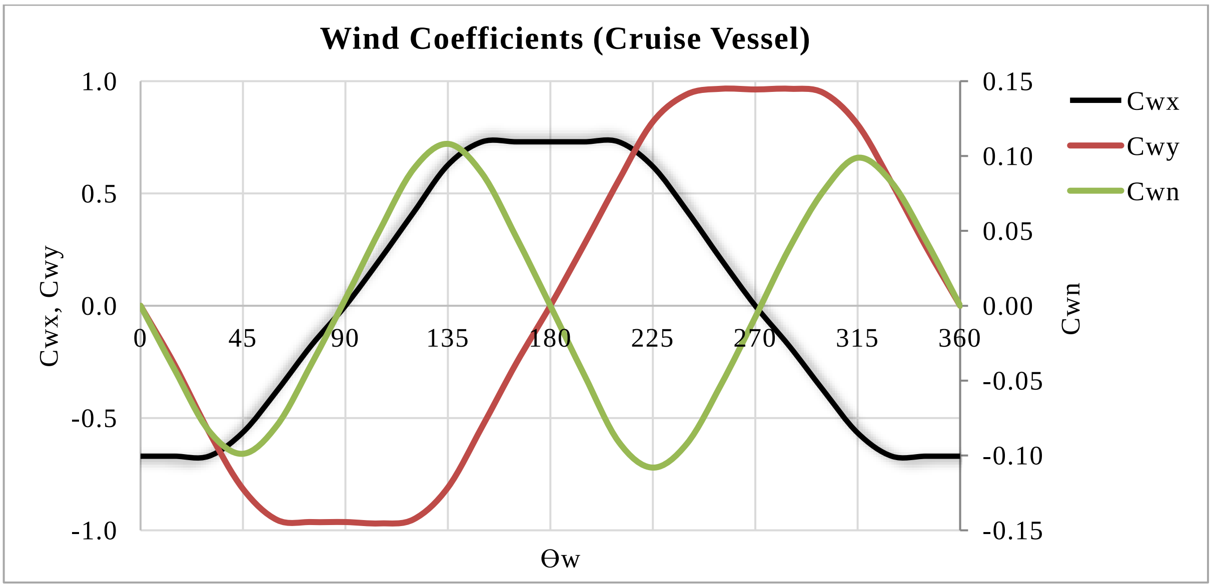

Fig. 48: Variation of wind surge, sway and yaw coefficients for cruise vessel with the direction

The DP plots are similar in terms of the capacity of winds that can be handled. The excel DP tool shows stepped variation in some regions where the values are significantly different from the Ref. curve. The Ref. curve is interpolated with the points at 15-degree intervals, whereas, the excel DP tool uses 5-degree increments. It is seen that both the graphs give very proximate results at 15-degree interval marks, which means that if the sensitivity of the ref. curve was to the same level of the excel tool, both the graphs would have been same. The DP capability represented by the black line shows greater capability in head and tailwinds which is normal considering the greater capacity of the propulsion system in controlling surge motions. Balance to beam wind conditions is also good as the obtained values hang about the 20 m/s mark

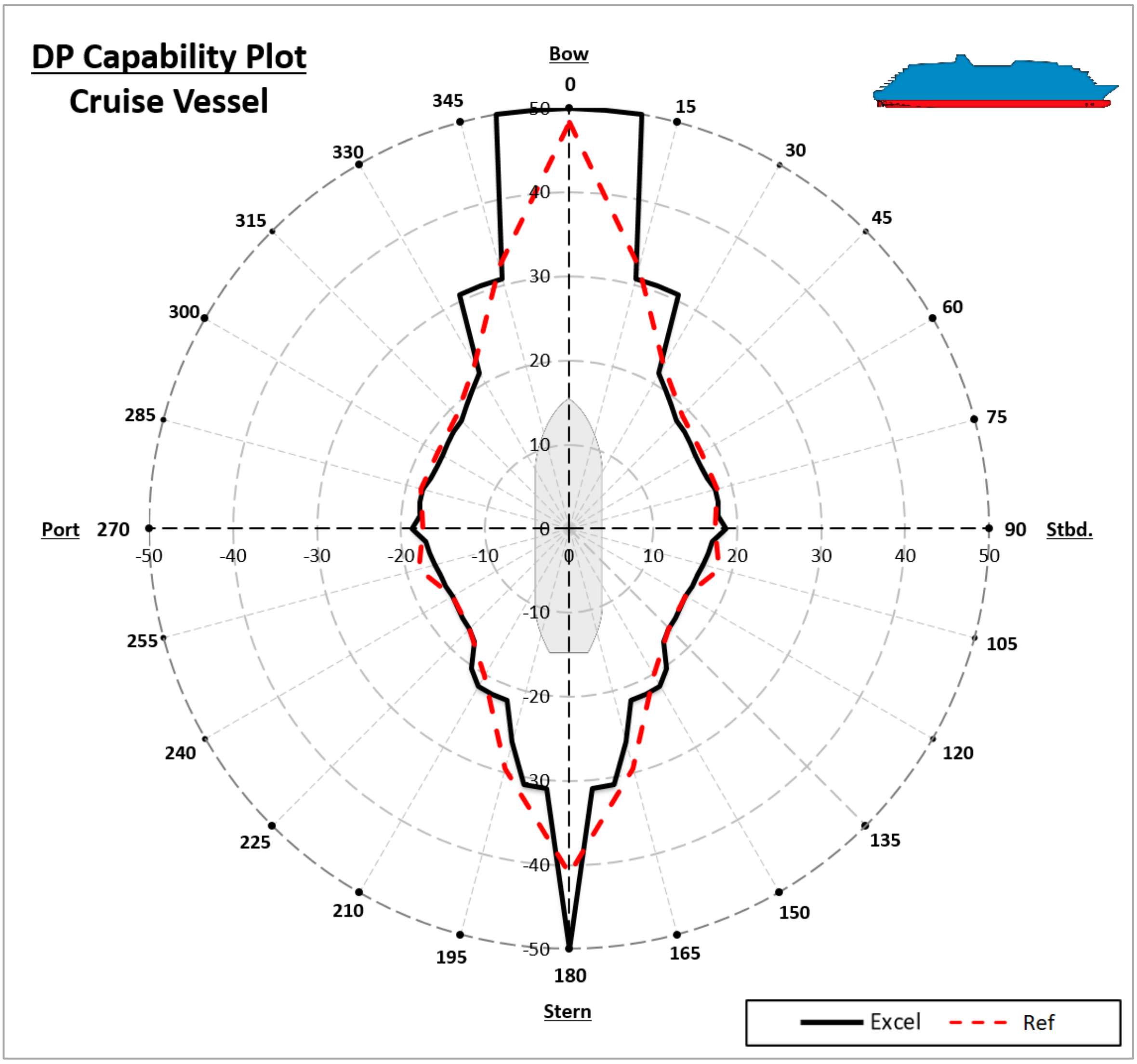

Fig. 49: Comparison of the DP capability plot obtained from excel DP tool with the reference

7.3 Conclusion from the validation study

It is evident from the validation study that the DP tool has the ability to meet the basic one-speed optimization of thrusts, as well as the complex optimization of objective functions with increased unknown variables over multiple loops. The robustness of the tool comes from the usage flexibility over various vessels and thruster configurations through suitable techniques and the ability to provide an automated representation of DP plots.

The thruster optimization for a single wind speed can be used in a progressive loop to check for increasing wind speeds until the full power has been utilized. This leads to the estimation of thruster response to external loads coming from a particular angle. This may be tried further in a larger envelope across various directions to find maximum sustainability with optimized thruster arrangements for each. Interpolation of such results give the DP plots. So, it is clear that ensuring the initial accuracy of the thrust optimization algorithm ensures the overall accuracy of the system and therefore leads to greater reliability of the DP Plots.

Testing for the various vessels has shown a sensible accuracy of the results. The overestimation and underestimation are avoided as the goal function continuously seek a self-opposing balance in terms of greater wind capacity with lower thrusts. So, a perfect static point can be obtained. Nevertheless, usage of DP tool in the initial design phase is always a challenge. Therefore, a trial and error procedure is undertaken, where the results are checked by multiple procedures and runs, and also physically interpreted, always keeping in mind the limiting factors that may render inaccuracy within the estimated values.

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8. CONCLUSION

A vast amount of researchers and calculation guidelines already exist on the design and optimization of the DP systems. The work focused on combining them in creating a reliable procedure to formulate easy-to-use module that can be effectively employed in the environment of the initial design phase for the calculation of DP capability. The present work, therefore, is a bridge between the theoretical studies and calculation data available in the market.

The task has been effectively disseminated into several goal based parts representing primary and secondary focus. The developed tool allows the estimation of the external forces, optimized thruster output to balance the loads, maximize DP capability over chosen thrusters and provide standard DP polar plots recognized throughout the industry. The optimization itself handles a complex array of design and load parameters to get to the result. It is clear that reliable DP assessment can be done at the very basic stage of the design process using only the basic set of parameters available at the stage. One great advantage of the use of the DP tool is the flexibility of use for vessels of any kind and over any arbitrarily defined conditions. The robustness of convergence of the optimization function adds to the ease of use making it a very convenient tool to deal with so many variables, yet providing satisfactory result. It is also a great advantage that user has the freedom of knowing and actively interacting with the actual working process, and not talking to a black box for result-feedback from given inputs.

A number of factors worthy of giving a second thought surfaced as a result of the present study. It is true that DP estimation is method specific. It might be enough to mention the methods, but to ensure a certain degree of reliability, a combination of methods must be used before deciding on the thruster configurations. The availability of various methods for each of wind, current and waves as well as different propulsion types allow the comparison of several methods within a single working platform. This is a huge benefit considering the fact that most of the tools available on DP at present are based either on single propulsion arrangement or on a single working methodology and does not allow taking both into account at the same time.

The thesis describes the study, development procedures and handling of the challenges for accomplishing the technical task of creating the DP tool. Initial design stage is the most crucial part of the design of a DP vessel. So, it is essential that due attention is paid to the performance and cost determinants for a good functionality in the long run.

8.1 Reference to Future Works

The present study deals only with the estimation of DP in the initial design stage. This is in fact only a small part in consideration to the whole DP system and arrangements required by a functional DP vessel. Nevertheless, due to immense importance of the designing phase, it is highly recommended to develop methods to ensure greater dependability on the estimated results.

It is clear from the present study that there are many scopes for further enhancement of the DP tool. It is very easy to integrate new calculation methods into the estimation process. The main direction of development should focus on further increase of accuracy and reliability of the results as well as the prediction of external forces and interaction effects. The methods for estimating wind and current loads seem sufficient, but it is necessary to develop more accurate methods to predict the behavior of second order wave drift loads. The calculation models for each vessel types are required in order to estimate the respective coefficients with a greater degree of reliability.

The assumptions made on the vessel particulars, variation of area and drafts, interaction effects etc. need to be taken into studied by the help of experimental techniques or CFD tools to develop methodologies to include their effects in the calculation process. Some of the sources date back to the 60’s, the shape and capability changed a great deal by this time, so the empirical relation based on those data must be updated. Formulation of a DP tool requires knowledge from various scientific fields, so a unified knowledge and tool development is essential for creating a better calculation tool.

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EMShip 7th Cohort Masters Student

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11. APPENDIX

A1. IMCA calculation of wind load:

Formula for calculating wind loads on hull:

Surge Load, $$F_{wx}(hull) = \frac{1}{2}\rho V_w^2 C_{wx}(\alpha_w) A_T(hull) \quad (27)$$

Sway Load, $$F_{wy}(hull) = \frac{1}{2}\rho V_w^2 C_{wy}(\alpha_w) A_L(hull) \quad (28)$$

Yaw Load, $$F_{wn}(hull) = \frac{1}{2}\rho V_w^2 C_{wn}(\alpha_w) A_L(hull) LBP \quad (29)$$

Coefficients,

$$C_{wx}(\alpha_w) = 0.423\cos(\alpha_w) \quad (30)$$

$$C_{wy}(\alpha_w) = 0.8\sin(\alpha_w) \quad (31)$$

$$C_{wn}(\alpha_w) = -0.143\sin(2\alpha_w) \quad (32)$$

Formula for calculating wind loads on superstructure:

Surge Load, $$F_{wx}(ss) = C_w (C_s C_h A_T(ss)) v_w^2 \quad (33)$$

Sway Load, $$F_{wy}(ss) = C_w (C_s C_h A_L(ss)) v_w^2 \quad (34)$$

Yaw Load, $$F_{wn}(ss) = F_{wy}(ss) X_{wc} \quad (35)$$

C_w = API wind coefficient (0.615×10^{-3} to give force in kN)
C_s = shape coefficient
C_h = height coefficient
$A_T(ss)$ = superstructure transverse projected area
$A_L(ss)$ = superstructure longitudinal projected area

For intermediate headings:

$$F_w(\alpha_w) = F_{wy}(90)\left[\frac{2\sin^2(\alpha_w)}{1+\sin^2(\alpha_w)}\right] + F_{wx}(0)\left[\frac{2\cos^2(\alpha_w)}{1+\cos^2(\alpha_w)}\right] \quad (36)$$

A3. DNV-GL calculation of wind load:

Formula for calculating wind loads on ship above water:

Surge Load, $$F_{X,wind} = \frac{1}{2}\rho_{air} V_{wind}^2 A_{F,wind} * (-0.7 * \cos(direction)) \quad (37)$$

Sway Load, $$F_{Y,wind} = \frac{1}{2}\rho_{air} V_{wind}^2 A_{L,wind} * (0.9 * \sin(direction)) \quad (38)$$

Yaw Load, $$M_{Z,wind} = F_{Y,wind} * \left(x_{L,air} + 0.3 * \left(1 - 2 * \frac{dir}{\pi}\right) * L_{pp}\right) \quad (39)$$

Direction, $$dir = \begin{cases} direction, 0 \leq direction \leq \pi, \\ 2\pi - direction, \pi \leq direction \leq 2\pi \end{cases} \quad (40)$$

A4. DNV-GL method of estimating thrust for actuators:

Formula for estimating thrust capacity from power:

Eff. thrust, $$T_{Effective} = T_{Nominal}\, \beta_T \quad (41)$$

Nom. thrust, $$T_{Nominal} = \eta_1 \eta_2 (D \times P)^{2/3} \quad (42)$$

Power, $$P = P_B \eta_M \quad (43)$$

Table 19: efficiency factor η_1

	η_1
Azimuths, pods and shaft line propellers	800
Cycloidal actuators	850
Tunnel thrusters	900
Contra-rotating azimuths, pods and shaft line propellers	950
Ducted azimuths, pods and shaft line propellers	1200

Table 20: $\eta 2$ for tunnel thrusters

	η_2
For broken inlets with $\alpha \in [20,50]$deg and $b > 0.1D$	1.0
For rounded inlet with $r > 0.05D$	1.07
For all other inlet shapes	0.93

— α is angle between tunnel wall and cone.
— b is the smallest breadth of the cone.
— r is the smallest radius of the rounding.
— D is propeller diameter.

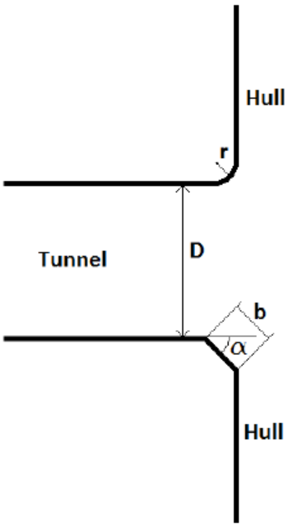

Fig. 50: Inlet and outlet of tunnels

Table 21: The efficiency factor η_2 for actuators other than tunnel thrusters

	η_2
Forward thrust	1.0
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

Table 22: Mechanical efficiency

	η_M
Cycloidal actuators	0.91
Tunnel and azimuth thrusters	0.93
Permanent magnet actuators	1.0*
Shaft line propellers	0.97
Pods	0.98
*The rated power shall be the brake power of the "propeller shaft". This means that the electrical losses and friction shall be accounted for in the rated power.	

A5. DP calculation results summary for the multipurpose vessel:

Table 23: Summary of DP Capability Calculation

DP Capability Plot (Summary)

Project: Multipurpose Vessel **Rev.** 0

Summary of DP Calculations

Angle	Vw	Hs	Tz	Vc	Fx	Fy	Mz	Time	Comment
0	50.00	22.87	10.02	0.51	-1460	0	0	12:25:31	OK!
5	50.00	22.87	10.02	0.51	-1424	-528	-10032	12:25:38	OK!
10	50.00	22.87	10.02	0.51	-1387	-1100	-21808	12:25:44	OK!
15	40.06	16.72	9.17	0.51	-912	-1164	-21828	12:26:01	OK!
20	35.46	13.87	8.78	0.51	-693	-1240	-20300	12:26:24	OK!
25	32.05	11.76	8.49	0.51	-540	-1275	-19015	12:26:58	OK!
30	29.83	10.39	8.31	0.51	-434	-1288	-18314	12:27:37	OK!
35	28.55	9.59	8.20	0.51	-358	-1317	-17003	12:28:19	OK!
40	27.12	8.83	7.96	0.51	-295	-1347	-15647	12:29:05	OK!
45	25.76	8.12	7.72	0.51	-241	-1366	-14381	12:29:54	OK!
50	25.02	7.73	7.59	0.51	-194	-1395	-12884	12:30:46	OK!
55	24.33	7.37	7.47	0.51	-153	-1419	-11536	12:31:38	OK!
60	23.73	7.09	7.41	0.51	-116	-1438	-10359	12:32:40	OK!
65	23.46	6.97	7.38	0.51	-80	-1458	-8922	12:33:31	OK!
70	23.18	6.84	7.36	0.51	-46	-1475	-7549	12:34:21	OK!
75	22.97	6.74	7.34	0.51	-13	-1498	-6284	12:35:17	OK!
80	22.99	6.75	7.34	0.51	17	-1520	-4847	12:36:03	OK!
85	23.00	6.76	7.34	0.51	47	-1538	-3395	12:36:53	OK!
90	22.99	6.75	7.34	0.51	78	-1555	-1938	12:15:28	OK!
95	23.27	6.88	7.36	0.51	106	-1576	-439	12:16:20	OK!
100	23.55	7.01	7.39	0.51	137	-1597	1149	12:20:16	OK!
105	23.87	7.16	7.42	0.51	169	-1622	2841	15:30:12	OK!
110	24.47	7.44	7.49	0.51	202	-1645	4462	15:22:47	OK!
115	25.20	7.82	7.62	0.51	239	-1672	6288	15:21:03	OK!
120	25.93	8.21	7.75	0.51	280	-1692	8310	15:24:07	OK!
125	27.14	8.84	7.96	0.51	328	-1718	10150	15:25:14	OK!
130	28.44	9.53	8.19	0.51	383	-1742	12315	15:26:23	OK!
135	29.48	10.17	8.28	0.51	447	-1770	14776	15:27:34	OK!
140	29.73	10.32	8.30	0.51	477	-1630	15128	15:38:53	OK!
145	32.83	12.24	8.56	0.51	625	-1818	19191	15:32:14	OK!
150	35.72	14.03	8.81	0.51	762	-1851	22625	15:40:02	OK!
155	39.56	16.41	9.13	0.51	940	-1847	24462	15:36:31	OK!
160	43.36	18.76	9.45	0.51	1133	-1738	25406	15:37:16	OK!
165	46.53	20.72	9.72	0.51	1311	-1488	24799	15:42:05	OK!
170	48.03	21.65	9.85	0.51	1400	-1044	17530	12:57:55	OK!
175	44.39	19.40	9.54	0.51	1233	-459	7581	15:44:36	OK!
180	45.15	19.87	9.60	0.51	1282	0	0	15:46:46	OK!
185	44.39	19.40	9.54	0.51	1233	-459	7581	15:44:36	OK!
190	48.03	21.65	9.85	0.51	1400	-1044	17530	12:57:55	OK!
195	46.53	20.72	9.72	0.51	1311	-1488	24799	15:42:05	OK!
200	43.36	18.76	9.45	0.51	1133	-1738	25406	15:37:16	OK!
205	39.56	16.41	9.13	0.51	940	-1847	24462	15:36:31	OK!
210	35.72	14.03	8.81	0.51	762	-1851	22625	15:40:02	OK!
215	32.83	12.24	8.56	0.51	625	-1818	19191	15:32:14	OK!
220	29.73	10.32	8.30	0.51	477	-1630	15128	15:38:53	OK!
225	29.48	10.17	8.28	0.51	447	-1770	14776	15:27:34	OK!
230	28.44	9.53	8.19	0.51	383	-1742	12315	15:26:23	OK!
235	27.14	8.84	7.96	0.51	328	-1718	10150	15:25:14	OK!
240	25.93	8.21	7.75	0.51	280	-1692	8310	15:24:07	OK!
245	25.20	7.82	7.62	0.51	239	-1672	6288	15:21:03	OK!

DP Capability Plot (Summary)

Project: Multipurpose Vessel **Rev.** 0

Summary of DP Calculations (Contd.)

Angle	Vw	Hs	Tz	Vc	Fx	Fy	Mz	Time	Comment
250	24.47	7.44	7.49	0.51	202	-1645	4462	15:22:47	OK!
255	23.87	7.16	7.42	0.51	169	-1622	2841	15:30:12	OK!
260	23.55	7.01	7.39	0.51	137	-1597	1149	12:20:16	OK!
265	23.27	6.88	7.36	0.51	106	-1576	-439	12:16:20	OK!
270	22.99	6.75	7.34	0.51	78	-1555	-1938	12:15:28	OK!
275	23.00	6.76	7.34	0.51	47	-1538	-3395	12:36:53	OK!
280	22.99	6.75	7.34	0.51	17	-1520	-4847	12:36:03	OK!
285	22.97	6.74	7.34	0.51	-13	-1498	-6284	12:35:17	OK!
290	23.18	6.84	7.36	0.51	-46	-1475	-7549	12:34:21	OK!
295	23.46	6.97	7.38	0.51	-80	-1458	-8922	12:33:31	OK!
300	23.73	7.09	7.41	0.51	-116	-1438	-10359	12:32:40	OK!
305	24.33	7.37	7.47	0.51	-153	-1419	-11536	12:31:38	OK!
310	25.02	7.73	7.59	0.51	-194	-1395	-12884	12:30:46	OK!
315	25.76	8.12	7.72	0.51	-241	-1366	-14381	12:29:54	OK!
320	27.12	8.83	7.96	0.51	-295	-1347	-15647	12:29:05	OK!
325	28.55	9.59	8.20	0.51	-358	-1317	-17003	12:28:19	OK!
330	29.83	10.39	8.31	0.51	-434	-1288	-18314	12:27:37	OK!
335	32.05	11.76	8.49	0.51	-540	-1275	-19015	12:26:58	OK!
340	35.46	13.87	8.78	0.51	-693	-1240	-20300	12:26:24	OK!
345	40.06	16.72	9.17	0.51	-912	-1164	-21828	12:26:01	OK!
350	50.00	22.87	10.02	0.51	-1387	-1100	-21808	12:25:44	OK!
355	50.00	22.87	10.02	0.51	-1424	-528	-10032	12:25:38	OK!
360	50.00	22.87	10.02	0.51	-1460	0	0	12:25:31	OK!

A7. North-sea wind-wave correlation (IMCA):

Table 24: Wind speed and wave height relation from North-Sea correlation by IMCA

Sig. Wave Height Hs (m)	Crossing Period, Tz (s)	Peak Period Tp (s)	Mean Wind Speed, Vw (m/s)
0	0	0	0
1.28	4.14	5.3	2.5
1.78	4.89	6.26	5
2.44	5.72	7.32	7.5
3.21	6.57	8.41	10
4.09	7.41	9.49	12.5
5.07	8.25	10.56	15
6.12	9.07	11.61	17.5
7.26	9.87	12.64	20
8.47	10.67	13.65	22.5
9.75	11.44	14.65	25
11.09	12.21	15.62	27.5
12.5	12.96	16.58	30
13.97	13.7	17.53	32.5
15.49	14.42	18.46	35

A8. Worldwide scatter wind-wave correlation (DNV-GL):

Table 25: Beaufort scale, wind speed, wave height and period and corresponding current speed from world-wide scatter diagram for DNV-GL recommended method

Beaufort (BF) number	Beaufort description	Wind speed* [m/s]	Significant wave height [m]	Peak wave period [s]	Current speed [m/s]
0	Calm	0	0	NA	0
1	Light air	1.5	0.1	3.5	0.25
2	Light breeze	3.4	0.4	4.5	0.50
3	Gentle breeze	5.4	0.8	5.5	0.75
4	Moderate breeze	7.9	1.3	6.5	0.75
5	Fresh breeze	10.7	2.1	7.5	0.75
6	Strong breeze	13.8	3.1	8.5	0.75
7	Moderate gale	17.1	4.2	9.0	0.75
8	Gale	20.7	5.7	10.0	0.75
9	Strong gale	24.4	7.4	10.5	0.75
10	Storm	28.4	9.5	11.5	0.75
11	Violent storm	32.6	12.1	12.0	0.75
12	Hurricane force	NA	NA	NA	NA

* The wind speed is the upper limit of the mean wind speed 10 m above sea level for the given DP capability number. The given peak wave periods represent the 95% confidence interval found from the worldwide scatter diagram.

A9. Detailed results of thrust and angles for comprehensive plots:

Table 26: Dynamic capability estimation thrust and power data for multipurpose vessel

Dynamic Capability Estimation (Thrust and Power Data)

Project: Multipurpose Vessel **Rev.** 0

Results		0		5		10		15		20		25		30		35		40	
		T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]
TT No. 1	[kN]	-3	***24***	159	***1098***	262	***1809***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***
TT No. 2	[kN]	1	***4***	173	***1199***	262	***1810***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***
AT No. 1	[kN]	226	***1324***	180	***1055***	250	***1462***	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***
	[deg]	0		7		67		92		90		95		95		93		92	
AT No. 2	[kN]	649	***3795***	632	***3697***	687	***4019***	513	***2999***	568	***3322***	608	***3558***	570	***3337***	586	***3425***	616	***3601***
	[deg]	0		2		1		45		0		0		3		6		8	
AT No. 3	[kN]	586	***3426***	632	***3696***	687	***4018***	558	***3265***	457	***2671***	477	***2792***	469	***2742***	502	***2935***	551	***3224***
	[deg]	0		13		29		0		74		96		104		115		124	

Dynamic Capability Estimation (Thrust and Power Data)

Project: Multipurpose Vessel **Rev.** 0

Results		45		50		55		60		65		70		75		80		85	
		T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]
TT No. 1	[kN]	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***
TT No. 2	[kN]	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***	270	***1867***
AT No. 1	[kN]	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***	260	***1521***
	[deg]	93		93		94		93		96		98		98		93		97	
AT No. 2	[kN]	598	***3498***	627	***3667***	642	***3757***	694	***4057***	694	***4057***	694	***4057***	694	***4057***	694	***4057***	694	***4057***
	[deg]	9		10		11		28		28		29		26		33		33	
AT No. 3	[kN]	579	***3386***	635	***3712***	679	***3973***	579	***3386***	606	***3547***	627	***3666***	694	***4057***	677	***3962***	694	***4057***
	[deg]	126		130		132		147		147		147		146		149		149	

Dynamic Capability Estimation (Thrust and Power Data)

Project: Multipurpose Vessel **Rev.** 0

Results		90		95		100		105		110		115		120		125		130	
		T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]
TT No. 1	[kN]	270	***1867***	270	***1867***	270	***1867***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***
TT No. 2	[kN]	270	***1867***	270	***1867***	270	***1867***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***
AT No. 1	[kN]	260	***1521***	260	***1521***	260	***1521***	260	***1520***	260	***1520***	260	***1520***	260	***1520***	260	***1520***	260	***1520***
	[deg]	100		99		99		100		96		91		98		92		97	
AT No. 2	[kN]	694	***4057***	694	***4057***	694	***4057***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***
	[deg]	36		39		42		45		50		55		57		64		67	
AT No. 3	[kN]	694	***4057***	694	***4057***	694	***4057***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***
	[deg]	149		150		151		152		153		155		153		155		154	

Dynamic Capability Estimation (Thrust and Power Data)

Project: Multipurpose Vessel **Rev.** 0

Results		135		140		145		150		155		160		165		170		175	
		T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]
TT No. 1	[kN]	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	255	***1762***	219	***1516***	-70	***481***
TT No. 2	[kN]	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	271	***1872***	250	***1729***	200	***1381***	271	***1872***
AT No. 1	[kN]	260	***1520***	260	***1520***	260	***1520***	260	***1520***	260	***1520***	260	***1520***	260	***1520***	-160	***1520***	-160	***1520***
	[deg]	98		95		98		93		100		132		157		0		0	
AT No. 2	[kN]	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4057***	694	***4060***
	[deg]	72		166		88		103		124		133		141		153		158	
AT No. 3	[kN]	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4060***	694	***4057***	-427	***4060***
	[deg]	153		72		152		147		137		135		140		153		0	

Dynamic Capability Estimation (Thrust and Power Data)

Project: Multipurpose Vessel **Rev.** 0

Results		180		Reverse/Min.		Forward/Max.		Max. Thrust	Max. Power	Available	Utilisation
		T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	T [kN]	P [kW]	Power [kW]	[%]
TT No. 1	[kN]	-27	***190***	-70	***481***	271	***1872***	271	***1872***	***2340***	**80%**
TT No. 2	[kN]	40	***278***	1	***4***	271	***1872***	271	***1872***	***2340***	**80%**
AT No. 1	[kN]	-160	***1520***	-160	***1520***	260	***1521***	260	***1521***	***1900***	**80%**
	[deg]	0									
AT No. 2	[kN]	694	***4060***	513	***2999***	694	***4060***	694	***4060***	***5075***	**80%**
	[deg]	181									
AT No. 3	[kN]	-427	***4060***	-427	***4060***	694	***4060***	694	***4060***	***5075***	**80%**
	[deg]	1									