Effect of propeller modelling on station-keeping thruster allocation strategy

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Abstract. In preliminary Dynamic Positioning calculations, quasi-steady prediction approach is commonly used to figure out the system capability. Thrust allocation solver is usually modelling the thruster devices as pure force generators, considering empirical general formulations to correlate delivered thrust with absorbed power. In such a way,a rough estimate of the power demand during station-keeping operations can be made. Once allocation algorithm is using minimum power demand as objective function, then a more precise modelling of the thrusters can be helpful since preliminary design stages. In the specific, by using an allocation algorithm capable to manage non-linear objective function and constraints, several types of propellers can be modelled, considering differences between tunnel thrusters and azimuthal thrusters, or the differences between fixed pitch and controllable pitch propellers. An example of the effect of propeller modelling is given, considering an Offshore Supply Vessel mounting steerable thrusters equipped with controllable pitch propellers, highlighting the differences with a standard allocation approach.

Keywords. Dynamic Positioning, thrust allocation, propeller modelling, non-linear optimisation

1. Introduction

The determination of Dynamic Positioning (DP) characteristics, necessary to assess the capability of station-keeping system installed on board of an offshore unit, is becoming nowadays a common analysis in the design process [1]. DP calculations can be executed with different levels of accuracy: a complete simulation of the system installed on board [2], a preliminary time domain simulation [3] and an easier quasi-steady one [4].
In the specific case of a preliminary DP study, the quasi-steady calculation techniques are preferred, since they require less information related to the analysed offshore unit. To perform a quasi-steady calculation, the balance between external, environmental and delivered thruster forces should be solved by means of a *thrust allocation* algorithm. This

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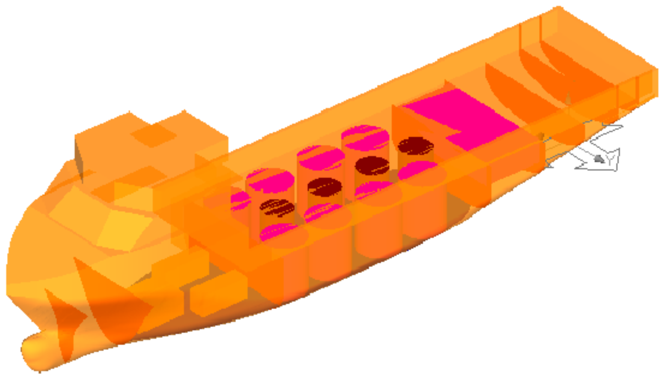

Figure 1. 3D representation of the modelled supply vessel.

procedure should be able to overcome the indetermination of the equilibrium system [5], which generally present more unknowns than solving equations. Despite the different levels of complexity presented by the available allocation algorithms [6], all the procedures are considering the thruster devices as pure thrust generators, using simple empirical formulations to convert propellers delivered thrust in absorbed power.
Since the target of an allocation algorithm is usually the absorbed power minimisation [7], simplified formulations have been adopted because of the resolution methods implemented, e.g. quadratic programming [8], require a particular objective function form. However, by adopting non-linear methods [6], it is possible to avoid formulation simplifications and use more realistic objective functions. In any case, to properly evaluate the power absorbed by the DP system, the cinematic and dynamic characteristics of the propellers should be determined. Once available data on the effective thruster behaviour are not present, the propellers can be modelled by means of systematic series [9], both in case of fixed pitch or controllable pitch installations.
This study will go through the description of propellers modelling on the specific case of an Offshore Supply Vessel (OSV), designed to be equipped with two propulsive controllable pitch azimuthal thrusters and two controllable pitch bow tunnel thrusters [10]. For the reference case, conventional propellers modelling and the new proposed one will be adopted, comparing the differences on the total absorbed power and capability plots, adopting a fully non-linear thrust allocation procedure.

2. The OSV reference ship

Through this study a reference vessel (Figure **??**) has been used to investigate the influence of propellers modelling on thrust allocation. The ship is an OSV designed to perform support duties to offshore platforms. For such a reason the vessel needs to have sufficient propulsive power for the transfer phase at a medium speed of 15 knots and should be equipped with bow thrusters to ensure sufficient DP capability for loading/offloading procedures nearby platforms. The main particulars of the vessel are reported in Table 1.
As mentioned the OSV is equipped with two propulsive steerable thrusters, mounting

Table 1. General particulars of the reference OSV.

Length between perpendiculars	L_{BP}	71.300	m
Length at design waterline	L_{WL}	75.420	m
Length overall submerged	L_{OS}	77.524	m
Breadth	B	16.000	m
Design draught	T	5.000	m
Volume	∇	3773.2	m^3
Wetted surface	S	1569.6	m^3
Bare hull wetted surface	S_0	1517.6	m^2
Appendages wetted surface	S_{APP}	52.0	m^2
Longitudinal centre of buoyancy	LCB	-1.4	$\%L_{BP}$
Block coefficient	C_B	0.630	-
Midship coefficient	C_M	0.940	-
Prismatic coefficient	C_P	0.660	-

controllable pitch propellers with a diameter of 2.4 m. Each thruster has a nominal power of 2050 kW at a propeller rotation rate of 250 rpm, being able to deliver a nominal thrust of about 677 kN. Each bow thruster has a nominal power of 1000 kW at a rotation rate of 260 rpm, having a diameter of 1.75 m, being able to develop a nominal thrust of about 147 kN. Also the bow thruster tunnel propellers are of controllable pitch type.

3. Standard DP calculation

To asses capability characteristics of a DP system in early design stage, quasi-steady calculations can be used to quickly asses the station-keeping quality by determining the capability plots. That means find the maximum sustainable wind speed that the DP system can face considering a constant collinear current speed and a wave load properly correlated with the incoming wind. That means solve for each wind speed and direction the following equilibrium system:

$$\begin{cases} \sum_{i=1}^{N} F_{x_i} = F_{x_{env}} \\ \sum_{i=1}^{N} F_{y_i} = F_{y_{env}} \\ \sum_{i=1}^{N} \left(-F_{x_i} y_{T_i} + F_{y_i} x_{T_i}\right) = N_{z_{env}} \end{cases} \tag{1}$$

where F_{x_i} and F_{y_i} are the forces generated by each of the N thrusters in x and y direction respectively, while x_{T_i} and y_{T_i} are the thrusters position coordinates. System 1 generally presents more unknowns than equations, leading to infinite possible solutions for the researched equilibrium. Classification societies or dedicated associations are not giving indications on the methods that should be used to solve the system and in literature a plenty of procedures are available [5], ensuring different levels of accuracy on the final solution [6]. Through this study a non-linear optimisation method has been applied, considering a non-linear objective function and non-linear constraints. With such a kind of modelling, the objective function is oriented to minimise the absorbed power. Then, the function to optimise becomes:

$$min\ f(x) = \sum_{i=1}^{N} x_i^{\frac{3}{2}} \tag{2}$$

being x_i the unknowns developed thrusts.
The objective function is subjected to the following constraints:

$$\begin{cases} T_{min_i} \leq T_i \leq T_{max_i} \\ \sum_{i=1}^{N} T_i \cos\theta_i = F_{x_{env}} \\ \sum_{i=1}^{N} T_i \sin\theta_i = F_{y_{env}} \\ \sum_{i=1}^{N} \left(-T_i \cos\theta_i y_{T_i} + T_i \sin\theta_i x_{T_i}\right) = N_{z_{env}} \end{cases} \tag{3}$$

where θ_i are the unknowns thruster orientation angles. It can be noticed that the first set of N constraints are the limitations in thrust of each thruster, while the last three are the equilibrium equations of system 1.

4. Propeller modelling

The vessel under consideration is, as mentioned, equipped by two azimuthal thrusters positioned at the vessel stern and two bow tunnel thrusters. All the listed devices are of the controllable pitch type. For such a reason, to improve the quality of the DP prediction, it is necessary to figure out a method able to describe the behaviour of a CPP. Once the dynamic characteristics of the thrusters propeller are not known a priori, then use can be made of systematic series. Data related to CPP are available thanks to the *CP-Series* developed by MARIN [9]. The series is composed by two propellers, one having a design $P/D = 1$ (propeller 4467) and the other $P/D = 0$ (propeller 4468). Both the propellers have been tested with different nozzle types, including the *Ka-Series* ones, means 19A, 22, 24 and 37, together with nozzle 38 designed for inland water tugs.
Between all the possible tested configurations of the *CP-Series*, the starting point for the modelling of a bow tunnel thruster and of a steerable thruster could be identified. Being a steerable thruster essentially also a propulsive device, the basis of the modelling can be given by the propeller 4467 with nozzle 19A. In such a way a propulsive thruster can be easily identified. Regarding the bow thruster tunnel propeller it must be underlined that in this case the propeller is not designed for propulsive issues and so can be modelled with propeller 4468. To simulate the tunnel it has been chosen to proceed with the most neutral nozzle of the available set, means nozzle 37.
Being these propellers and nozzles not exactly the same of the commercial thrusters, it is necessary to empirically correct the dynamic propeller curves by means of four coefficients:

$$\lambda_T = \frac{K_T}{K_{T_0}}; \lambda_Q = \frac{K_Q}{K_{Q_0}}; e_T = \left.\frac{J}{J_0}\right|_{K_T}; e_Q = \left.\frac{J}{J_0}\right|_{K_Q} \tag{4}$$

where λ_T is used to change the bollard pull value of the thrust coefficient, λ_Q for the torque coefficient and e_T and e_Q are used to change the operating range of the thruster on thrust and torque respectively. In Figure 2 an example is given of the modelling of the steerable thrusters equipped on the analysed OSV, starting from propeller 4467 equipped with nozzle 19A.
By adopting this kind of modelling for the steerable thruster and a comparable one for the bow thruster, but starting from propeller 4468 with nozzle 37, it is possible to establish

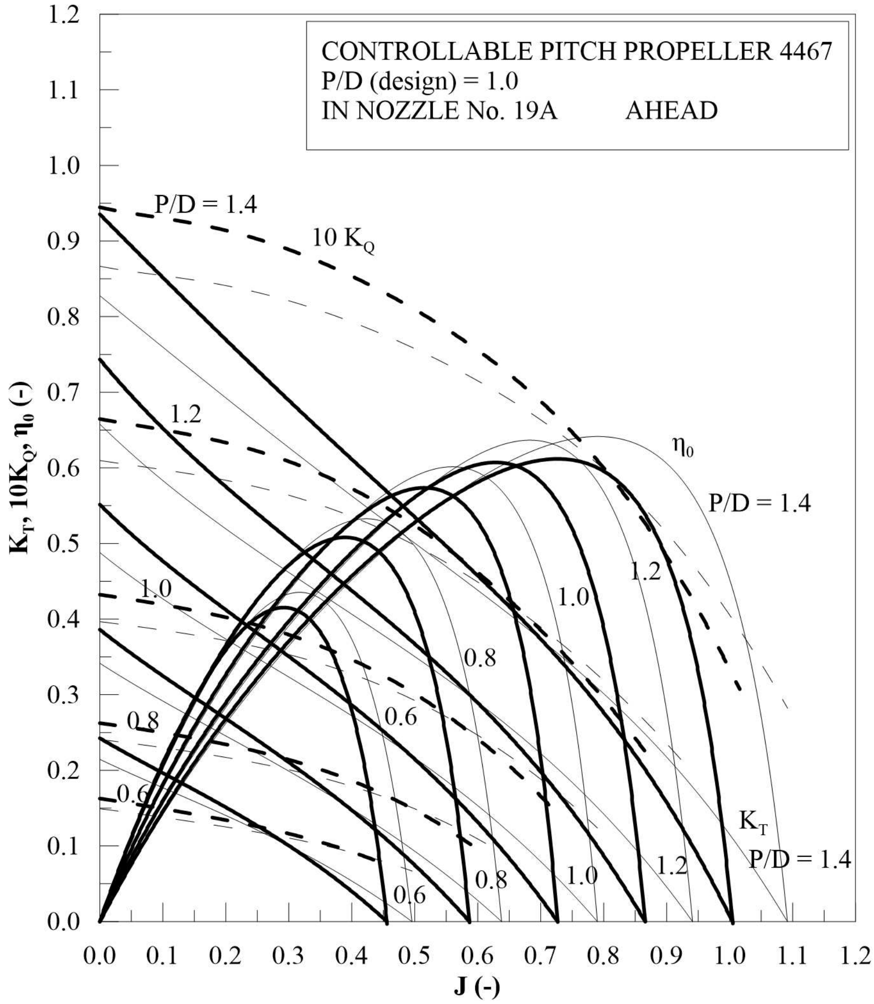

Figure 2. Open water diagrams of the steerable thruster (*bold*) installed on the OSV, compared to 4467 propeller with nozzle 19A.

the *thrust/power* relationships for the devices installed on board. It can be stated that a thruster during DP operation is working really close to bollard pull condition, so the determination of the desired relationship can be restricted to the specific bollard pull case. To define the thrust/power curve, use can be made of empirical relationships available in literature as:

$$P = \frac{1}{D}\left(\frac{T}{1.2}\right)^{1.5} \tag{5}$$

$$P = \frac{1}{D}\left(\frac{T}{1.082}\right)^{1.5} \tag{6}$$

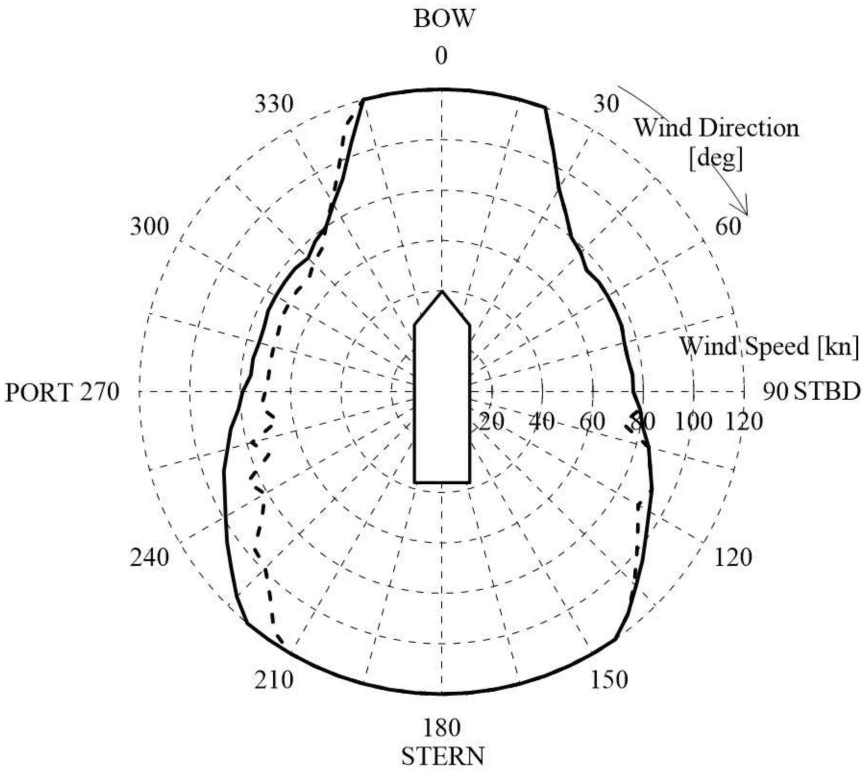

Figure 3. DP capability plot for the OSV considering a traditional (*continuous*) or an enhanced (*dashed*) propeller modelling.

being equations 5 and 6 representative of a steerable thruster and of a bow thruster tunnel respectively. Analysing the two equations it can be observed that the equation shape is reflecting the objective function reported in equation 2, which represents the standard way to treat power in non-liner optimisation solvers for DP thrust allocation.

Considering a more detailed modelling of the CPP, the relationships between power and thrust will change. According to the above mentioned cases of the OSV vessel, the following relationships can be found for bollard pull operations, fitting the bollard pull curves:

$$P = 0.4424T^{1.42} \tag{7}$$

$$P = 0.6359T^{1.43} \tag{8}$$

$$P = 1.5543T^{1.29} \tag{9}$$

the above equations are representative of the steerable thruster and of the bow tunnel thruster in ahead and astern conditions respectively. All the equations are considering the power expressed in kW and the thrust in kN. As already mentioned, the tunnel thruster has different behaviours in astern and ahead conditions, means the maximum thrust delivered will not be the same in the two pull directions.

Considering equations 7, 8 and 9 it is possible to modify the objective function 2, in such

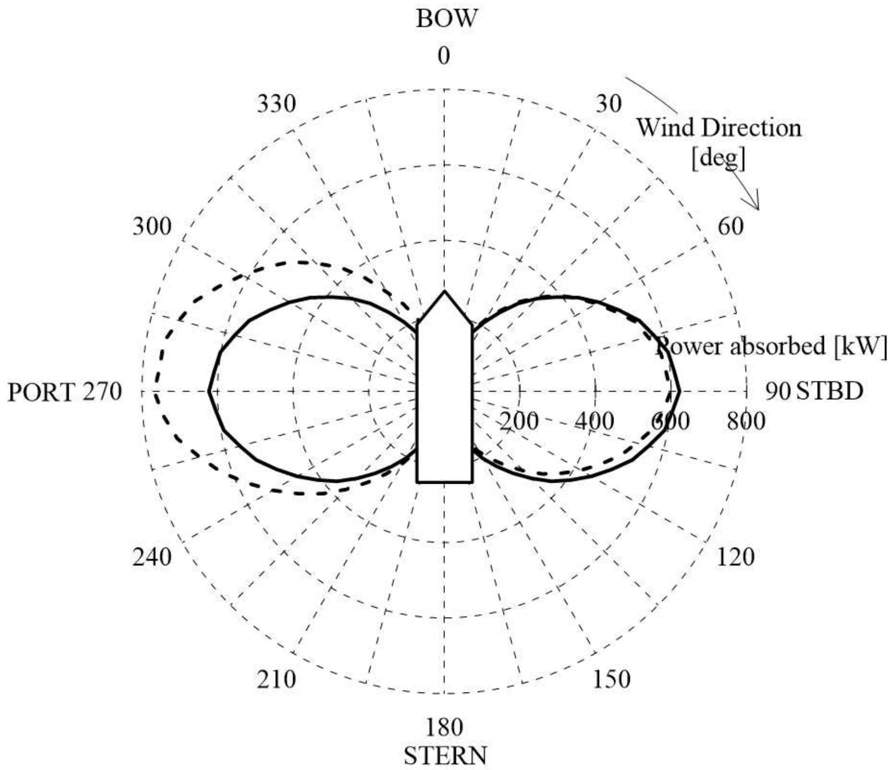

Figure 4. Total absorbed power for the OSV considering a traditional (*continuous*) or an enhanced (*dashed*) propeller modelling considering a wind speed of 20 knots.

a way to consider the proper propeller modelling directly inside the allocation algorithm. In this way, standard DP calculations can be performed and compared with the ones coming from the new propeller modelling. It is interesting to perform a comparison on the total capability of the system but also on some specific environmental cases. For such a reason a preliminary DP capability calculation has been performed with both methods to see the differences between the two proposed models on the final capability plot. For the specific a wind/wave correlation according to IMCA has been adopted. Thereafter, a dedicated calculation has been performed considering an intermediate environmental condition (not an extreme one as for the capability results) with a wind speed of 20 knots and a wave according to IMCA wind/wave correlation. The current has not be intentionally considered in such a way to justify the bollard pull assumption.
The obtained results for the capability plot are visible in Figure 3, where it is possible to observe the differences due to different modelling of ahead and astern conditions of the tunnel thruster, resulting in an asymmetrical capability plot. In Figure 4 the particular environmental condition of 20 knots of wind speed is considered. Here it is possible to visualise the total power absorbed at each encounter angle; by adopting the enhanced method a difference of about 5% is noted when bow thrusters are acting ahead (between 0 and 180 degrees) while the differences are growing up to 25% when the same thrusters are acting in astern condition (180 to 360 degrees).

5. Conclusions

The possibility to model different kind of controllable pitch propellers by means of general systematic data, available in literature, has been investigated on a reference OSV ship, mounting both steerable and fixed thrusters. The corrections used to match the nominal propeller characteristics given by the constructors, allow to reproduce in a more accurate way the relationships between delivered thrust and absorbed power. The implementation of the obtained relationships directly in the allocation algorithm allows to capture the differences between the behaviour of the bow tunnel thrusters in ahead or astern condition, highlighting an asymmetry on the final capability plot. Also the possibility to define in a more accurate way the total absorbed power in every specific environmental condition will be for sure an added value in the evaluation of the total power used in each phase of vessel operation. It can be stated that a even more detailed thruster modelling, including also current effect on the propeller inflow and thruster-thruster interaction can be a possible source of even further improvements in total absorbed power determination during DP operations, and will be for sure the further step of the here presented study.

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