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Local optimization of thruster configuration based on a synthesized positioning capability criterion

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ABSTRACT: *DPCap analysis can assist in determining the maximum environmental forces the DP system can counteract for a given heading. DPCap analysis results are highly affected by the thrust forces provided by the thrust system which consists of several kinds of thrusters. The thrust forces and moment are determined by the maximum thrust of the thrusters as well as the thruster configuration. In this paper, a novel local optimization of thruster configuration based on a synthesized positioning capability criterion is proposed. The combination of the discrete locations of the thrusters forms the thruster configuration and is the input, and the synthesized positioning capability is the output. The quantified synthesized positioning capability of the corresponding thruster configuration can be generated as the output. The optimal thruster configuration is the one which makes the vessel has the best positioning capability. A software program was developed based on the present study. A local optimization of thruster configuration for a supply vessel was performed to demonstrate the effectiveness and efficiency of the program. Even though the program cannot find the global optimal thruster configuration, its high efficiency makes it essentially practical in an engineering point. It may be used as a marine research tool and give guidance to the designer of the thrust system.*

KEY WORDS: DPCap; Synthesized positioning capability; Local optimization of thruster configuration.

INTRODUCTION

A Dynamically Positioned (DP) vessel is by the International Maritime Organization (IMO) and the certifying class societies (DNV, ABS, LR, etc.) defined as a vessel that automatically maintains its position and heading (fixed position or pre-determined track) exclusively by means of active thrusters. Dynamic Positioning System (DPS) has been widely used in offshore engineering over the last five decades. Description of DPSs, including their early history can be found in Fay (1990) and Morgan (1978).

Operation safety is always the first consideration in the design and operation of a new DPS. To be able to plan a safe and efficient operation, it is important to know the window of operation, and the maximum environmental conditions the particular DP vessel can withstand. During critical operations such as drilling, oil production and offloading, the positioning precision requirements are high, regardless of the environmental conditions. It is thus important to know the positioning capability of the vessel in order to plan and execute operations in a safe manner, according to Pivano et al. (2012). It is necessary to perform a

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Dynamic Positioning Capability (DPCap) analysis when designing a new DP vessel.

DPCap analysis can assist in determining the maximum environmental forces the DP system can counteract for given headings, see IMCA (2000). Mostly DPCap analysis investigates the dynamic positioning capability of the vessel from 0° to 360° headings. The environmental forces and moment are statically balanced by thrust forces and moment provided by the thrust system which consists of several kinds of thrusters. The positioning capability is determined by the maximum thrust of the thrusters as well as the thruster configuration.

In the design of a thrust system, there are many factors are subject to changing (i.e. the number of the thrusters, the thruster types, the maximum thrust of the thruster and the thruster configuration, etc.). Many efforts can be found in literature focus on the selection of the thrusters and their configuration. Mahfouz and El-Tahan (2006) has proposed a developed software program as a marine tool in the selection of thrusters, in their configuration, and during preliminary investigation of the positioning ability of a newly designed vessel dynamic positioning system. However, the comparison of a vessel's positioning capability is based on the rough observation of the polar plots, which may cause confusion when these polar plots overlap with each other. Xu et al. (2015a) has proposed a synthesized positioning capability criterion which can quantify the synthesized positioning capability to avoid confusion. The synthesized criterion is adopted to compare the polar plots.

In this paper, the optimization of thruster configuration based on the synthesized positioning capability criterion is focused. The optimization of thruster configuration has been studied in the aircraft area (Hwang et al., 2003; Servidia and Sanchez Pena, 2002 etc.) and in the underwater vehicle area, see Pierrot et al. (1998). However, little effort can be found in the optimization of the thruster configuration for marine surface vessels. Since the thruster configuration is essentially important to the thrust system, an efficient optimization tool is essential to be developed. Based on the local optimization method, one can improve the synthesized positioning capability of the vessel.

The thruster's location region is formed by the feasible locations of the thruster. The thruster's location region is split up into some discrete locations. It is satisfied that the distance of any neighboring locations is less than or equal to a given interval tolerance. The discrete locations of all thrusters are combined to form the thruster configuration, which can be regarded as input of trials. When the number of the thrusters is large, the number of combinations of the thruster locations is significantly large. Since the DPCap analysis and synthesized positioning capability computation should be performed for every thruster configuration, it's significantly time-consuming to conduct the global optimization.

The local optimization of thruster configuration attempts to change only one thruster's location from its discrete locations' set at a time, then conduct the DPCap analysis and compute the synthesized positioning capability. The best synthesized capability corresponding location of the thruster is recorded. A software program was developed based on the present study. The effectiveness and efficiency of the program was demonstrated by a local optimization of thruster configuration for a supply vessel.

DPCAP ANALYSIS

DPCap analysis can assist in determining the maximum environmental forces the DP system can counteract for given headings. The accuracy of DPCap analysis is determined by the precise estimation of the environmental forces as well as the effectiveness of the thrust allocation logic. Estimation of the environmental forces can be based on model tests, hydrodynamic computation and empirical formulas, as addressed in Sørensen (2001). Thrust allocation logic can be formulated as an optimization problem, where the objective typically is to minimize the use of control effort (or power) subject to actuator rate and position constraints, power constraints as well as other operational constraints, see Johansen et al. (2004) and Fossen and Johansen (2006). Many methods for optimization are available in literature and quadratic programming method has been demonstrated to be relatively effective and robust, see De Wit (2009).

Wind, wave and current are assumed coincident in direction when one conduct a DPCap analysis. The forces and moment due to each component are evaluated individually and summed to evaluate the total steady-state environmental forces and moment, as described in API (1987). CFD method can be implemented to evaluate the wind loads, see Gosman (1999) and Zhang et al. (2010). The second order mean wave loads can be obtained based on quadratic transfer functions, as addressed in Newman (1977) and Faltinsen (1990). Estimation of the current loads can be found in literature: e.g. Kim et al. (2009), Vaz et al. (2009) and Leite et al. (1998).

A flow chart of DPCap analysis is presented in Fig. 1. Given the current heading of the vessel (initially 0), environmental forces and moment are estimated based on the current wind velocity (initially 0). The environmental forces and moment are balanced by the applied forces and moment, which are provided by the thrust system. Thrust allocation logic determines the optimal solution to generate the applied forces and moment. If the optimal solution exists, the severity of the environmental conditions is increased and the above procedures are repeated until an optimal solution no longer exists. (It should be noted that bisection search method can be used to search the maximum environmental condition in order to improve the efficiency, as proposed in Xu et al. (2015b).) The previous wind velocity is saved for the current heading. If not all the headings have been completed, move to the next heading and repeat all above procedures until all headings are completed. Finally, the polar plot of the vessel is generated based on the heading-dependent wind velocities.

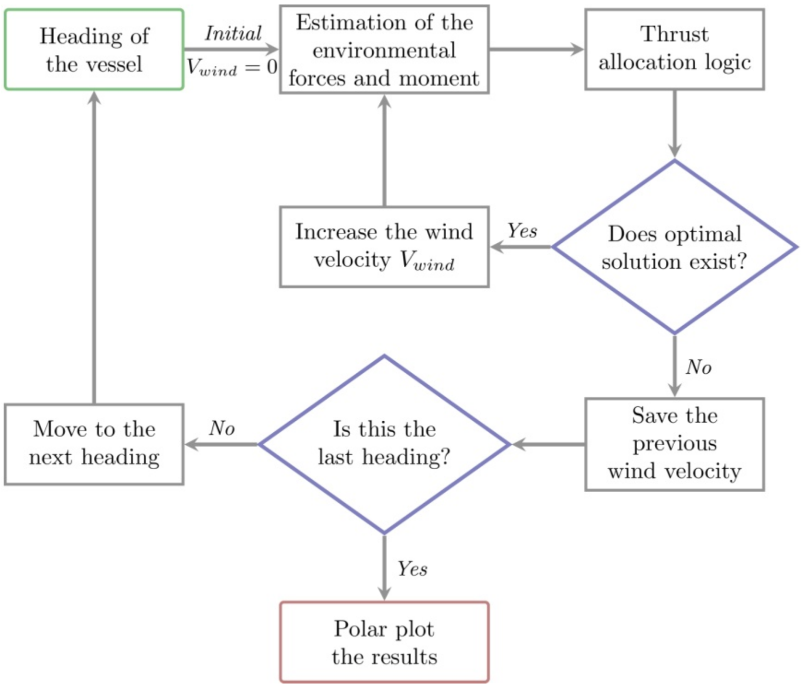

Fig. 1 Flow chart of DPCap analysis.

SYNTHESIZED POSITIONING CAPABILITY CRITERION

In DPCap analysis it may be possible to compare positioning capability results in different cases. In some circumstances, the results can be distinguished by direct observation of the polar plots. However, for overlapping polar plots, there may be confusion in selecting which case has the better positioning capability. Even though the better case is selected according to one's preference, other factors such as the stability of the positioning capability cannot be accounted for. Thus, a quantified synthesized positioning capability criterion is essential for a direct and accurate comparison. The synthesized positioning capability is determined by the overall mean positioning capability as well as the stability of the vessel heading-dependent capability.

Overall mean positioning capability

The overall mean positioning capability can be modelled by the expectation of the positioning capabilities (usually represented by wind velocity limits). The expectation value can be obtained by integrating the product of the heading-dependent positioning capability and the vessel's heading probability density function over a given operation heading interval. The operation heading interval $[\psi_{start}, \psi_{end}]$ is composed of the headings of the vessel relative to the direction of the environmental conditions. An example of the operation heading interval is given in Fig. 2. The overall mean positioning capability can be represented by Eq. (1).

$$Cap_{mean} = \mu = \int_{\psi_{start,}}^{\psi_{end}} P(\psi)V_{\omega}(\psi)d\psi \tag{1}$$

where $\psi_{start,}$ and ψ_{end} are the counterclockwise headings of the vessel, and satisfy $0 \le \psi_{start} < \psi_{end} \le 2\pi$. $V_{\omega}(\psi)$ is the wind velocity limit dependent on the heading of the vessel ψ. $V_{\omega}(\psi)$ can be generated by DPCap analysis and is usually presented in polar format. $P(\psi)$ is a heading probability density function dependent on the heading ψ to the environmental forces.

$P(\psi)$ can be represented by

$$P(\psi_i) = \frac{C_i}{\sum_{i=1}^{N} C_i},\ \psi_i \in (\psi_i - \frac{\delta\psi}{2}, \psi_i + \frac{\delta\psi}{2}) \tag{2}$$

where ψ_i is an arbitrary heading of the vessel, $\delta\psi$ is a small quantity of ψ. The smaller the quantity of $\delta\psi$, the more precise of the obtained heading probability density function. C_i is the number of counts of the heading during long-term (likely 1 year) observation for a specific frequency (likely to be 1 count per minute). By use of Table 1, $P(\psi)$ can be obtained by a long-term observation of the vessel's heading in field tests.

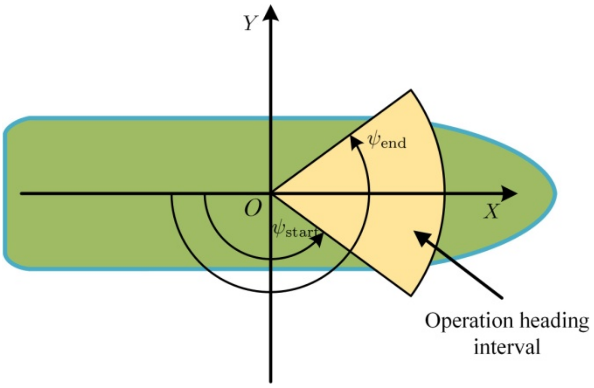

Fig. 2 Example of a given operation heading interval.

If no field test results can be obtained, the probability of the heading can be assumed to be constant in the given operation heading interval (i.e. $C_i = \text{Constant}$ in Eq. (2)). $P(\psi)$ can be represented by

$$P(\psi) = \frac{1}{|\psi_{end} - \psi_{start}|},\ \psi \in [\psi_{start}, \psi_{end}] \tag{3}$$

Eq. (3) is a particular case of Eq. (2).

Table 1 Example of statistics for the heading of the vessel ($\delta\psi = 5°$).

Heading (°)	170	175	180	185	190
	±2.5	±2.5	±2.5	±2.5	±2.5
Counts	C_1	C_2	C_3	C_4	C_5

The values of ψ_{start} and ψ_{end} depend on the specific requirements of the vessel's engineering application. Although the positioning capabilities from $0°$ to $360°$ are investigated during DPCap analysis, the only positioning capabilities of concern are the specific headings in the operation heading interval. For a particular vessel operated in a specific maritime zone, the headings of the vessel are usually constrained in a fixed interval. However, the probabilities of the headings in the interval are different. The probability density function $P(\psi)$ accounts for the probability of every heading in the given operation heading interval, which makes the modelled overall mean positioning capability more realistic.

Stability of the capabilities

The stability of the heading-dependent capabilities can be modelled by an item formed by the standard deviation and the expectation of the capabilities in the given operation heading interval. The stability of the capabilities can be represented by Eq. (4).

$$Cap_{stab} = e^{-\frac{\sigma}{\mu}} \tag{4}$$

$$\sigma = \sqrt{\int_{\psi_{start}}^{\psi_{end}} P(\psi)(\mu - V_{\omega}(\psi))^2 d\psi} \tag{5}$$

where σ and μ are the standard deviation and the expectation of $P(\psi)V_{\omega}(\psi)$ in the operation heading interval $[\psi_{start}, \psi_{end}]$, respectively. The heading probability density function $P(\psi)$ is also considered in the formulation of σ .

The stability of the capabilities in the given operation heading interval is important for evaluating the synthesized positioning capability of the vessel. With a positioning capability of high stability, the vessel can maintain relatively steady positioning when its heading oscillates, which makes the operation safer.

Synthesized criterion

The synthesized positioning capability is determined by the overall mean positioning capability as well as the stability of the vessel heading-dependent capability. A possible synthesized criterion can be derived from a product of the overall mean positioning capability and the stability of the capabilities. Eq. (6) gives the formula of the synthesized positioning capability criterion.

$$Cap_{cri} = Cap_{mean} Cap_{stab}^{\lambda} = \mu \times e^{-\lambda \frac{\sigma}{\mu}} \tag{6}$$

where λ is the weight factor of Cap_{stab} in the synthesized positioning capability criterion. λ can be increased to give greater weight to the capability stability of the synthesized positioning capability criterion when the vessel requires higher capability stability for safe operation.

The synthesized positioning capability criterion can be used to compare the synthesized positioning capabilities of DP vessels. Actually, for an arbitrary DPCap polar plot, the synthesized capability can be obtained from Eq. (6), which makes the criterion more applicable. For instance, the criterion can be used for comparison of vessels with different thruster configurations or comparison of vessels with different thruster failure modes.

LOCAL OPTIMIZATION OF THRUSTER CONFIGURATION

The thruster configuration is formed by the selection of thrusters and locations of the thrusters. A good thruster configuration can assist the thrust system in producing sufficient thrust forces and moment simultaneously. However, a poor thruster configuration may assist the thrust system in resisting the surge or sway forces, cannot assist in resisting the environment moment. Thus, the synthesized positioning capability of the vessel is highly influenced by the thruster configuration.

The optimization of the thruster configuration assumes that the initial thruster configuration is determined, whereas the coordinates of thrusters can fluctuate around its initial location. Thus, the optimization is based on the fundamental design of the thruster configuration. It is a supplementary procedure dedicated to optimizing the synthesized positioning capability subject to the thrusters' location regions.

Thrusters' location region

The location regions of thrusters are formed by the fluctuation of the coordinates of the thrusters. The magnitude and direction of the fluctuations are constrained by the realistic requirements of deployment of the equipment on the vessel. Generally, the tunnel thruster and azimuth thruster are deployed in the middle longitudinal plane (i.e. $y = 0$). The y coordinate of the main thruster (propeller) is constrained by the stern structure of the vessel and is usually fixed. Therefore, the fluctuation is always in the x direction. The thrust region of the i -th thruster can be represented by

$$x_i^L \le x_i \le x_i^H, \tag{7}$$

where x_i^L and x_i^H are the low and high bounds of the coordinates of the i -th thruster, respectively. An example of the location regions of the thrusters is given in Fig. 3.

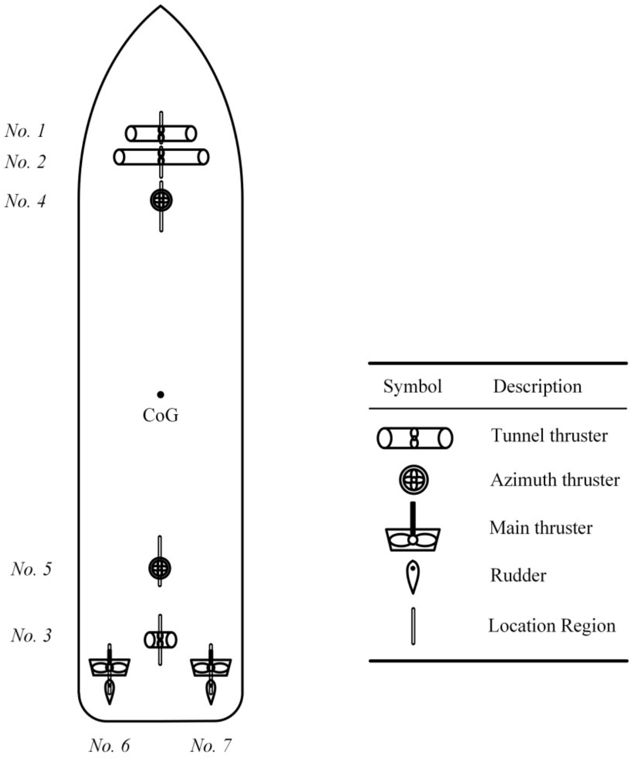

Fig. 3 The location regions of thrusters and thruster configuration for a supply vessel.

Discrete location region

In order to conduct the DPCap analysis and compute the synthesized positioning capability, the coordinates of all thrusters should be prepared beforehand. The location regions should be split up into discrete locations based on a given interval tolerance ε . It is satisfied that the distance of any neighboring locations is less than or equal to the given tolerance. The number of the *i*-th thruster's discrete locations can be obtained by

$$n_i = \left\lceil \frac{x_i^H - x_i^L}{\varepsilon} \right\rceil + 1 \tag{8}$$

where $\lceil \cdot \rceil$ means taking ceiling of the number. The j-th coordinate of the i-th thruster's discrete locations can be represented by

$$x_i^j = x_i^L + (j-1)\cdot\frac{x_i^H - x_i^L}{n_i}, \tag{9}$$

where $j = 1, 2, ..., n_i$. The smaller the interval tolerance is, the larger the number of the coordinates is. The number of thruster configurations required to conduct the optimization by use of the global optimization method can be obtained by

$$N = \prod_{i=1}^{n} n_i, \tag{10}$$

where n is the number of freedoms of the thrusters. If only one direction (x or y direction) of the thruster requires to be optimized, the number of freedoms is one. If both x and y directions of the thruster needs to be optimized, the number of freedom is two. Since the DPCap analysis and synthesized positioning capability computation should be performed for every thruster configuration, it's significantly time-consuming to conduct the global optimization. Consequently, a simplification should be made to solve this problem.

Local optimization of thruster configuration

The location region of thrusters is split up into discrete locations. The combination of the locations of thrusters forms the thruster configuration. Based on the DPCap analysis and synthesized criterion, the synthesized positioning capability of the corresponding thruster configuration can be achieved. However, it will be time-consuming to investigate all the thruster configurations. A local optimization method can solve this problem efficiently.

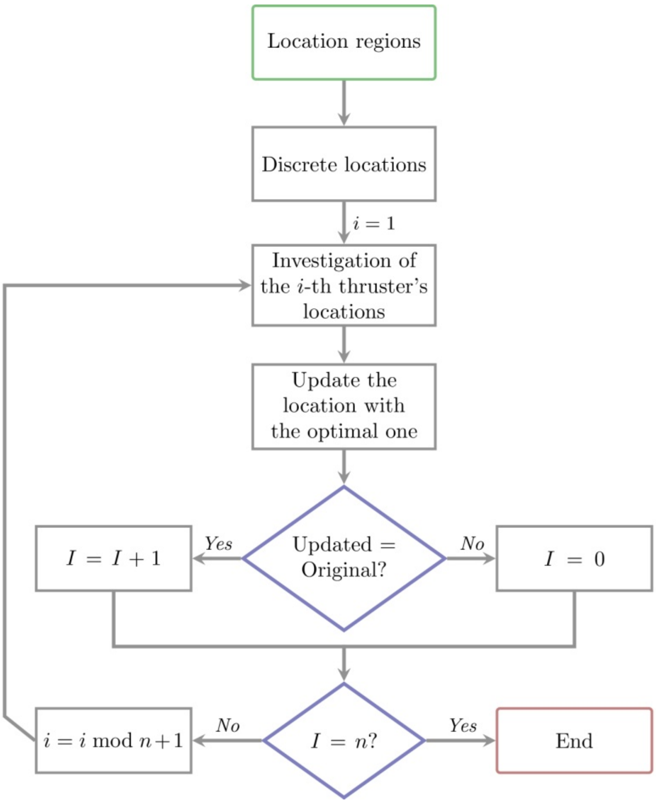

Fig. 4 Diagram of the local optimization of the thruster configuration.

By use of the local optimization method, the coordinates are investigated thruster by thruster, and the thrusters remain their initial coordinates except the being investigated thruster's coordinate. In optimization of a thruster's coordinate, its initial coordinate will be updated by the coordinate that makes the vessel has the best positioning capability, for the next thruster's investigation. Once all the thrusters' coordinates are equal to the updated coordinates, the optimization ends and the optimal thruster configuration is yielded. Since the aforementioned investigation can't find the global optimal solution, it is named as a local optimization method. A diagram of the local optimization of thruster configuration is given in Fig. 4.

NUMERICAL ANALYSIS

Overview of the analysis

The coordinate system is fixed to the vessel body with the origin located at the mean oscillatory position in the average water plane with X axis points towards bow, Y axis points towards port and Z axis points towards upwards. The relative environment angle, α , is positive anti-clockwise starting from the stern. Moments are positive anti-clockwise. The coordinate system is illustrated in Fig. 5.

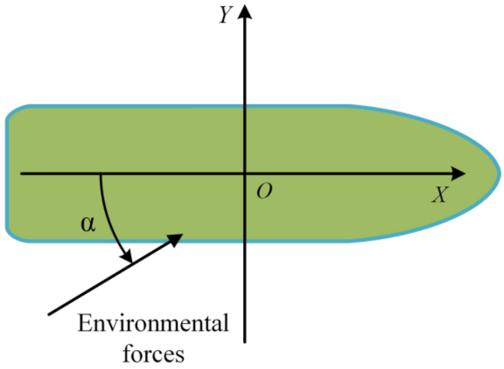

Fig. 5 Coordinate and notations.

A local optimization of thruster configuration for a supply vessel was conducted to evaluate its performance on finding the optimal thruster configuration. Parameters of the supply vessel are tabulated in Table 2. The initial thruster configuration is illustrated in Fig. 4. The shape of the supply vessel is shown in Fig. 6. The curves for the wind (10 *m/s*), current (1 *m/s*) and wave (Hs. = 10 *m*) forces with respect to heading angle are given in Fig. 7. The wind, current and wave forces are proportional to the square of the wind velocity, the square of the current velocity and the square of the significant wave height, respectively. The maximum thrust and location regions of thrusters are tabulated in Table 3. Eighty percent of the maximum available thrust is used in DPCap analysis. The reserved twenty percent is considered to be used in resisting dynamic environmental loads. The location tolerance was selected as 1 *m*. The locations of the main thrusters should be the same for any thruster configuration. Wind and current forces and moment were estimated by a model test conducted in the State Key Laboratory of Ocean Engineering (SKLOE). Wave forces and moment were estimated by CFD method. The current velocity was 1 knot in DPCap analysis, as recommended by IMCA (2000). The operation heading intervals were set as $[3\pi/4, 5\pi/4]$ and $[2\pi/3, 4\pi/3]$, respectively.

Table 2 Parameters of the supply vessel.

Items	Values
Draft (*m*)	6.5
Displacement (*t*)	8849
Overall length (*m*)	92.8
Moulded breadth (*m*)	22.6
L.C.G (from C.L.) (*m*)	0.32
T.C.G (from C.L.) (*m*)	0
V.C.G (from B.L.) (*m*)	8.17

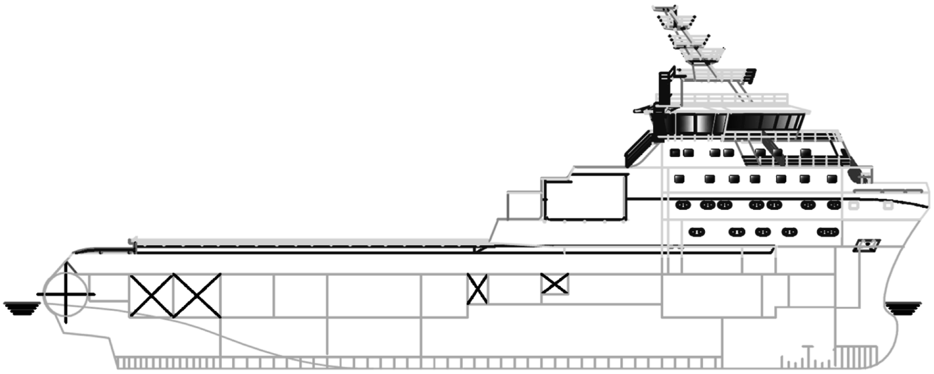

Fig. 6 The shape of the supply vessel.

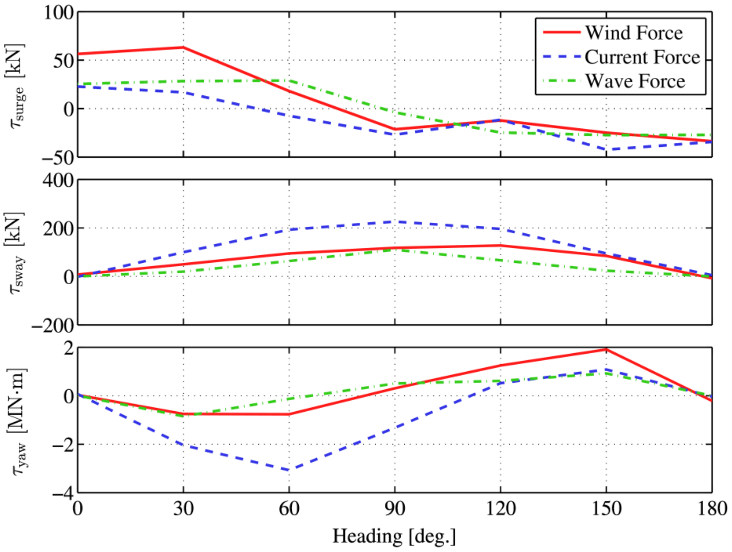

Fig. 7 The curves for the wind (10 *m/s*), current (1 *m/s*) and wave (Hs. = 10 *m*) forces with respect to heading angle.

Table 3 Maximum thrust and location region of each thruster.

Thruster	Max. Thrust (*kN*)	x^L (m)	x^H (m)	y^L (m)	y^H (m)
NO. 1	137	70	76	0	0
NO. 2	137	60	66	0	0
NO. 3	137	-66	-60	0	0
NO. 4	180	50	56	0	0
NO. 5	180	-56	-50	0	0
NO. 6	480	-74	-70	-22	-18
NO. 7	480	-74	-70	18	22

A newly self-dependently developed program in SKLOE was adopted to perform the DPCap analysis. Thruster-thruster interaction was not considered since the long distance between the two azimuth thrusters. The main thruster with rudder can be operated in both forward and reverse modes.

The synthesized positioning capability criterion was adopted to quantify the synthesized capabilities of the vessel. $P(\psi) = 1/\left|\psi_{end} - \psi_{start}\right|$ in all cases, as no probability density function can be obtained.

Results and discussions

By use of the program, the optimal thruster configuration and the best synthesized positioning capability are obtained. The optimization course of thruster configuration is shown in Table 4, given the operation heading interval $[3\pi/4, 5\pi/4]$. The case corresponding to operation heading interval $[2\pi/3, 4\pi/3]$ has the similar optimization course and results, which are not shown in this paper for simplicity. The optimal thruster configuration is given in Table 5. 14 steps are needed to obtain the local optimal thruster configuration (i.e. when the indicator $I = 7$). Since the two main thrusters must have the same coordinate in x direction, there are only 6 thrusters really available to be optimized. For the main thrusters, since their locations in y direction should also be optimized, the total freedom for the main thrusters is two. In every step, the corresponding thruster region as shown in Table 3 requires to be spilt into discrete locations based on the given location tolerance, and for any discrete location the DPCap analysis and synthesized positioning capability need to be performed and select the best positioning capability corresponding discrete location for the following thruster's optimization. Starting from step 8, the optimal thruster configuration remains the same with the previous one, the indicator I increase one for every step until its value is equal to the number of freedoms of active thrusters. Thus, the local optimal thruster configuration is obtained.

Table 4 The optimization course of thruster configuration, given the operation heading interval $[3\pi/4, 5\pi/4]$.

Step	Active thruster	Thruster coordinates (x, y), (m)							Cap_{cri}	I
		NO. 1	NO. 2	NO. 3	NO. 4	NO. 5	NO. 6	NO. 7	(-)	
Initial	-	(72, 0)	(65, 0)	(-65, 0)	(55, 0)	(-55, 0)	(-72, 20)	(-72 ,-20)	64751	0
1	NO. 1	(76, 0)	(65, 0)	(-65, 0)	(55, 0)	(-55, 0)	(-72, 20)	(-72 ,-20)	64995	0
2	NO. 2	(76, 0)	(66, 0)	(-65, 0)	(55, 0)	(-55, 0)	(-72, 20)	(-72 ,-20)	65122	0
3	NO. 3	(76, 0)	(66, 0)	(-60, 0)	(55, 0)	(-55, 0)	(-72, 20)	(-72 ,-20)	65679	0
4	NO. 4	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-55, 0)	(-72, 20)	(-72 ,-20)	65736	0
5	NO. 5	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 20)	(-72 ,-20)	66127	0
6	NO. 6&7	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 20)	(-72 ,-20)	66363	0
7	NO. 6&7	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	0
8	NO. 1	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	1
9	NO. 2	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	2
10	NO. 3	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	3
11	NO. 4	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	4
12	NO. 5	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	5
13	NO. 6&7	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	6
14	NO. 6&7	(76, 0)	(66, 0)	(-60, 0)	(56, 0)	(-50, 0)	(-72, 22)	(-72 ,-22)	66831	7

Table 5 The optimal thruster configuration.

Thruster	Coordinates (m)
NO. 1	(76, 0)
NO. 2	(66, 0)
NO. 3	(-60, 0)
NO. 4	(56, 0)
NO. 5	(-50, 0)
NO. 6	(-70, 22)
NO. 7	(-70, -22)

In the optimal thruster configuration, the thrusters on the vessel tends to approach to the bow direction. This phenomenon may be caused by the unbalance of the thrust which can be supplied in the bow and stern. In the optimization of the thruster configuration, trying to generate more moment in yaw direction, the thrust system attempts to balance the supplied thrust on the bow and stern.

Employing the local optimization of thruster configuration, the synthesized positioning capability improved 3% (from 64751 to 66831). Moreover, the total thrust consumed by the thrust system decreased 2%. Even though the improvement of the synthesized positioning capability and the reduction of the total thrust is very small, the local optimization of thruster configuration is still promising due to its high efficiency. It may give guidance to the designer of the thrust system.

CONCLUSIONS

In this study, a local optimization of thruster configuration based on a synthesized positioning capability criterion was proposed. A numerical example is given by an optimization of the thruster configuration for a supply vessel. From the obtained results, one can optimize the thruster configuration for a marine surface vessel by use of the local optimization method. The new method may need a further validation by a real project.

Even though the program cannot find the global optimal thruster configuration, its high efficiency makes it essentially practical in an engineering point. It may be used as a marine engineering tool to give guidance to the designer of the thrust system.

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