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Discussion on Methods and Influence Factors for Minimum Propulsion Power Assessment

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Abstract: Currently, the International Maritime Organization (IMO) has approved and implemented the assessment requirement for Minimum Propulsion Power (MPP) of ships in adverse sea conditions. The assessment method and relevant influence factors will have a vital impact on ship's design and operation. On the other hand, MPP is essentially a criterion for manoeuvring safety at actual seas. However, the practical assessment methods adopted in IMO guidelines do not directly and accurately account for ship's course-keeping ability in severe seas. A time-domain comprehensive method with supplementary course-keeping ability criteria has been proposed in the authors' preliminary research. Based on an updated mathematical model and criteria, this paper presents more detailed elaborations, results and discussions on the time-domain method, including the comparative analyses with a power line method and two steady-state equilibrium methods based on IMO guidelines and draft. Discussions on the influences of key factors, involving criterion conditions and calculation parameters, are also presented. The results indicate that different methods exhibit varying advantages and complexity in MPP assessment, thus constituting a multi-level assessment framework for MPP. In particular, the time-domain comprehensive assessment has a higher accuracy with more realistic description of manoeuvre behaviors, capable of offering a solution for the ships that cannot meet other assessments, or for the assessment requiring additional course-keeping ability. Furthermore, an expanded range of wave direction sets a stricter but potentially necessary requirement, while using the self-propulsion factors at low speeds can eliminate the unnecessary conservation of assessment result caused by those at design speed.

Key words: manoeuvrability in actual seas; minimum propulsion power; comprehensive assessment; manoeuvrability criterion; course keeping

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0 Introduction

Reducing installed power is the most effective and straightforward way to comply with the mandatory regulation of Energy Efficiency Design Index (EEDI). However, this raises the concerns about unfavorable influences on manoeuvrability with navigational risks for low-powered ships. On this background, the concept and demand of Minimum Propulsion Power (MPP) to maintain manoeuvrability in adverse

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conditions have been proposed by the International Maritime Organization (IMO). Originally in 2013, the interim guidelines[1] were released for checking the installed power of large- and medium-sized transport vessels, with the adoption of both the level-1 assessment through a minimum power line, and the level-2 simplified assessment using a longitudinal single-degree-of-freedom (1DOF) steady-state equilibrium equation. Over the years, several research findings and proposals regarding the amendments of the interim guidelines were submitted to IMO, including the definitions of adverse conditions and speed requirement, as well as the determination methods of added wave resistance and self-propulsion factors at extremely low speed. By 2021, the final revised guidelines[2] had been adopted. In addition, the level-3 comprehensive assessment had ever been proposed by solving three-degree-of-freedom (3DOF) equilibrium equations[3], and the requirement of maximum course deviation was raised at the same time. Nevertheless, it has not been approved in formal guidelines due to its complexity of practical implementation.

The MPP guidelines regulate the manoeuvring safety for newly-built and existing ships, and principally serve for simplified and practicable engineering evaluations. However, they cannot replace performance-based assessments for ships near the acceptance boundaries or for unconventional vessels[4]. It was also pointed out at the 29 th International Towing Tank Conference (ITTC)[5] that the simplified assessment should be validated by enhanced and comprehensive methods. Moreover, clear criteria and measures for course-keeping ability are essential for manoeuvring safety assessment, while the MPP guidelines only indirectly address it by verifying the navigational speed.

In addition to the regulation development, the majority of relevant research[6−7] on MPP assessment in the past decade has concentrated on the applications of existing guidelines through example calculations and analyses. As for research on comprehensive assessment, some studies[4,8] solved practical steady-state equilibrium equations to obtain required thrust and brake power in steady sailing conditions. Other researchers[9−10] performed time-domain simulations by using sophisticated mathematical model to investigate the effect of engine power on manoeuvrability in adverse conditions. The authors' previous work[11−12] has primarily focused more on MPP assessment problem itself, proposing a novel time-domain assessment procedure that involves direct MPP calculation and better accounts for the additional course-keeping ability criteria. On the whole, current efforts in comprehensive assessment are still insufficient.

This paper presents a more in-depth and refined analysis of the authors' preliminary research, offering more detailed elaborations and extended discussions on the proposed level-3 3DOF Time-Domain (TD) method. The mathematical model for manoeuvring motion is updated, including a newly-proposed combined method for calculating wave added resistance. Responding to the recommended work proposed by ITTC to validate simplified methods, three assessment methods based on IMO guidelines and documents are realized and compared to the time-domain method, i.e., the Minimum Power Line (MPL) method for level-1 assessment, the 1DOF Steady-state Equilibrium (SE) method for level-2 assessment, and the 3DOF SE method for level-3 assessment as well. Furthermore, the investigations on several important influence factors, including criterion conditions and calculation parameters, are conducted and discussed. IMO continues to monitor and review the implementation of existing guidelines. Some comments and proposals in this study can support the ongoing development in this field.

1 Assessment scenario and criteria

The original IMO interim guidelines and the 29 th ITTC mentioned that a ship should have the ability to maintain a certain advance speed, and to keep/change course in all the unfavourable wave and wind directions under adverse sea conditions. The current revised guidelines addressed the criteria including maintaining a minimum forward speed of at least 2 kn, and keeping heading over wind and wave directions from head to 30° off-bow for a situation of weather vaning. However, it is important to emphasize that the revised guidelines do not explicitly establish direct and detailed correlations for ship's course-keeping ability.

It was preliminarily verified by the authors that the course-keeping manoeuvre, especially in oblique waves, sets stricter demands on engine power than course-changing manoeuvre. Therefore, this study only focuses on the course-keeping manoeuvre as the concerned scenario. In accordance with the MPP guidelines, only manoeuvring in open sea and deep water is considered.

With reference to the previous research and guidelines, the employed manoeuvrability criteria for MPP assessment are categorized into two aspects: the propulsion ability criterion and the course-keeping ability criterion, as outlined in Tab. 1. It is important to note that these criteria are not completely independent but actually interconnected.

Tab.1 Employed criteria for MPP assessment

Criterion	Measure	Connotation
Propulsion ability criterion	Forward speed	Ability to timely leave from dangerous sea areas
Course-keeping ability criterion	Drift angle	Ability to control course and avoid unfavourable directions
	Rudder angle	Ability to reserve a steering margin

2 Time-domain comprehensive assessment method

2.1 Outline of mathematical model

Coordinate systems: As shown in Fig. 1, one coordinate system is the earth-fixed coordinate system O_0-$x_0y_0z_0$, where the horizontal plane x_0y_0 coincides with the surface of still water. The other is the ship-fixed coordinate system O-xyz, whose origin is located at the crossing position of midship and ship's draft. Fig. 1 also shows the longitudinal forward speed u, lateral velocity v, resultant horizontal velocity U, yaw rate r, drift angle β, heading angle ψ, and rudder angle δ. The symbols χ_{W0} and χ_{A0} denote the absolute wave direction and wind direction in the earth-fixed system, respectively. The wind direction is assumed to be aligned with the wave direction. Both coordinate systems coincide at the initial time with $\psi = \beta = \delta = 0$.

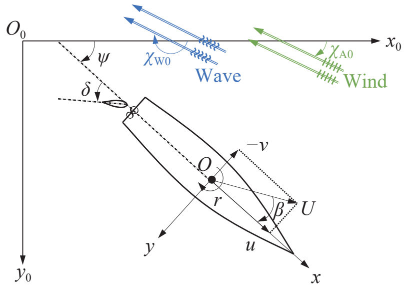


Fig.1 Coordinate systems of the mathematical model

Motion equations: Instead of the manoeuvring-seakeeping unified model built in the authors' previous research[11−12], a simpler and straightforward time-domain mathematical model for course-keeping manoeuvres in actual seas is established for MPP assessment. A group of system-based 3DOF motion equations considering disturbances induced by waves and wind is given by Eqs. (1a)–(1c), based on the Manoeuvring Modelling Group (MMG) standard model[13].

$$(m+m_x)\dot{u}-(m-m_y)vr-mx_{\mathrm{G}}r^2=X_{\mathrm{H}}+X_{\mathrm{W}}+X_{\mathrm{A}}+X_{\mathrm{R}}+X_{\mathrm{P}} \tag{1a}$$

$$(m+m_y)\dot{v}+(m+m_x)ur+mx_{\mathrm{G}}\dot{r}=Y_{\mathrm{H}}+Y_{\mathrm{W}}+Y_{\mathrm{A}}+Y_{\mathrm{R}} \tag{1b}$$

$$(I_{zz}+x_{\mathrm{G}}^2m+J_{zz})\dot{r}+(\dot{v}+ur)mx_{\mathrm{G}}=N_{\mathrm{H}}+N_{\mathrm{W}}+N_{\mathrm{A}}+N_{\mathrm{R}} \tag{1c}$$

where X, Y, and N denote the longitudinal force, lateral force, and yaw moment acting on the ship, respectively; the subscripts H, P, R, A, and W represent the hull hydrodynamic reaction force (moment) due to manoeuvring motion, propeller thrust, rudder force (moment), wind loads, and wave force (moment), respectively; m and I_{zz} are the ship's mass and yaw moment of inertia, respectively; m_x, m_y, and J_{zz} are the added masses and added moment of inertia; $\dot{u}$, $\dot{v}$, and $\dot{r}$ represent the accelerations. In this study, X_{H}, Y_{H}, N_{H}, X_{P}, X_{R}, Y_{R}, and N_{R} are expressed and calculated through the MMG standard model. Wind is assumed to be uniform in space and constant in time, and wind loads can be estimated using empirical formulas.

Wave drift force and moment: Short-crested irregular waves with $\cos^2$-directional spreading function are considered. Since MPP assessment focuses on the averaged statistical values of low-frequency manoeuvring motion at low speeds, the first-order wave-induced force and moment are neglected. It can be assumed that the second-order wave drift force and moment are time-harmonic and superposed by component regular waves, and they can be efficiently computed under the quasi-steady treatment, using the frequency-dependent steady longitudinal drift force (i.e., the added resistance in waves) coefficient $C_{\mathrm{W}X}$, lateral drift force coefficient $C_{\mathrm{W}Y}$, and yaw moment coefficient C_{WN} of the corresponding component wave. A frequency-domain database of these three coefficients is established over various directions, speeds, and frequencies, pre-calculated by using a panel method. Real-time three-dimensional interpolation within the database is carried out during simulations. Additionally, authors' pre-calculations have demonstrated that the slow drift effect caused by the difference-frequency component can be neglected, due to its little impact on the averaged statistical values.

A combined method for calculating $C_{\mathrm{W}X}$: Regarding the $C_{\mathrm{W}X}$ curve, the panel method may underestimate the peak region at intermediate and high speeds, as well as the short wavelength region. This is due to the imprecise solution for speed effect and viscous diffraction effect. Alternatively, a semi-empirical method, named the SNNM (SHOPERA-NTUA-NTU-MARIC) method, has been recently developed and officially recommended in the revised guidelines. However, the authors found that this method overestimates the results at low speeds in the regions of intermediate and long wavelengths, which is attributed to the exceedance of the formula's applicable scope when Froude number Fr <0.09. Therefore, motivated by the practical correction formulas from Tsujimoto et al[14], this study proposes a combined method that incorporates both the above methods, expressed by Eq. (2).

$$X_{\mathrm{W}}=\begin{cases}(1-\alpha_{\mathrm{d}})X_{\mathrm{W}}^{\mathrm{Panel}}+\alpha_{\mathrm{d}}X_{\mathrm{W}}^{\mathrm{SNNM}}, Fr<0.09\\ X_{\mathrm{W}}^{\mathrm{SNNM}}, Fr\geqslant 0.09\end{cases} \tag{2}$$

where $X_{\mathrm{W}}^{\mathrm{Panel}}$ and $X_{\mathrm{W}}^{\mathrm{SNNM}}$ denote the added resistance calculated by the panel method and SNNM method, respectively; α_{d} represents the combination coefficient, depending on encountered wave numbers. It should be noted that Eq. (2) is discontinuous at Fr =0.09. In spite of this unsatisfactory property, the combined method compensates for the deficiencies of the two methods above and can be regarded as a convenient and effective way to calculate X_{W}. This method has been verified by authors and showed good correction effect.

Engine and rudder controls: An Operational Limits of Engine (OLE) model[15] for a low-speed diesel engine is applied, including a torque/speed limit of engine. The operational point (output power and rotation rate) on the corresponding power curve falls always within the OLE. The classical Proportional-Integral-Differential (PID) controller is selected as an autopilot model to calculate the target rudder angle. Besides, the Line of Sight (LOS) guidance will be optionally applied to estimate the desired heading angle ψ_{d} and follow the desired path. More advanced control strategies are not extensively explored in this paper.

The framework of the mathematical model and numerical solution is depicted in Fig. 2.

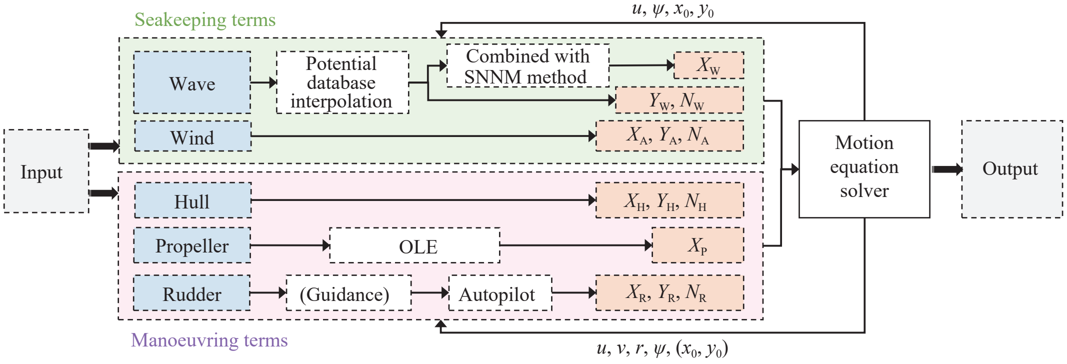


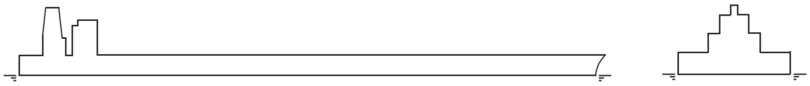
Fig.2 Framework of the time-domain mathematical model and numerical solution for manoeuvring in actual seas

2.2 Subject ship and simulation verification

The international benchmark tanker KVLCC2, equipped with a fixed-pitch propeller and a horn rudder, is taken as the subject ship. The full-scale principal particulars are listed in Tab. 2, where L, B, and d represents the length between perpendiculars, breadth, and draft, respectively; (x_G, y_G, z_G) are the coordinates of center of gravity; ∇ is the displacement volume; A_R is the profile area of the movable part of rudder; h_R is the rudder height; $\dot{\delta}$ and δ_{lim} are the rudder's turning rate and maximum allowable deflection angle, respectively; D_P is the propeller diameter. The main engine power is quantified by MCR (Maximum Continuous Rating). The symbol n_{MCR} represents the engine rotation rate corresponding to MCR, estimated by considering a 5% margin on the propeller rotation rate that attains the design speed U_0 in calm water [15]. The initial operational point is set as 95% n_{MCR}. Since KVLCC2 is not an actual built ship, an assumed deadweight (DWT) provided by ITTC[5] and approximate superstructure profiles[10] illustrated in Fig. 3 are utilized based on existing similar tankers. Other hydrodynamic parameters, such as manoeuvring derivatives, propeller- and rudder-related coefficients, are employed through existing experimental data[13].

Tab.2 Principal particulars of KVLCC2

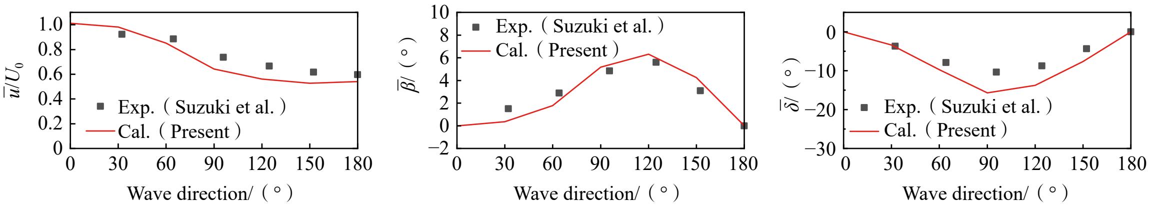
Item/Unit	L/m	B/m	d/m	(x_G, y_G, z_G)/m	∇/m^3	DWT/t	I_{zz}/(kg·m^2)
Value	320.00	58.00	20.80	(11.20, 0, −2.20)	312 622	302 273	1.89×10^{12}
Item/Unit	h_R/m	A_R/m^2	D_P/m	n_{MCR}/(r·min^{-1})	$\dot{\delta}$/(°/s)	δ_{lim}/(°)	U_0/(m·s^{-1})
Value	15.80	112.50	9.86	81.16	2.34	35.00	7.97



(a) Side profile (b) Front profile

Fig.3 Profiles of KVLCC2's hull and assumed superstructure above water surface

The free-running course-keeping manoeuvres are simulated to verify the reliability of the mathematical model and simulation codes. The experimental research on the tanker KVLCC1 performed by Suzuki et al[15] is used as reference. The main particulars of KVLCC1 are the same as those of KVLCC2, with similar manoeuvrability and slight modifications in stern shape. The employed autopilot parameters (k_P = 2 and k_I = k_D = 0) and environmental conditions (deep and open water area, mean wave period T_1 = 10.2 s, significant wave height H_S = 7.0 m, and mean wind speed U_{A0} = 22.7 m/s) remain consistent with the referenced experiment. The OLE is not considered in the verification in accordance with the model tests, and thereby, the constant rotation rate of propeller (n_P) to achieve the speed of U_0 is used. It should be noted that the applied superstructure and n_P (1.285 r/s) are slightly different from those in the experiments. The wake fraction $\omega_P = 0.35$ and the thrust deduction fraction $t_P = 0.22$[13] are used in present calculations. Thereupon, the averaged statistical results of the simulations are presented and compared with experimental data in Fig. 4. Overall, the verification results are regarded acceptable, given the complexity involved in the manoeuvring motion under waves and wind conditions.



（a）Mean forward speed （b）Mean drift angle （c）Mean rudder angle

Fig.4 Comparison of course-keeping manoeuvre calculation results with experiment data in short-crested irregular waves

2.3 Assessment procedures

The required brake power (MCR_{REQ}) in the assessment is considered as the value of MPP in this study. The elementary procedures of time-domain method to calculate MPP are proposed below. Firstly, series of time-domain course-keeping manoeuvres are conducted with various preset MCR and a predetermined n_{MCR} over the specified various wave directions and periods. The time-averaged forward speed $\bar{u}$, drift angle $\bar{\beta}$, and rudder angle $\bar{\delta}$ are obtained by solving Eqs.(1a)~(1c).

Then, the assessment criteria involving minimum forward speed $u_{\min}$, maximum drift angle $\beta_{\max}$, and maximum rudder angle $\delta_{\max}$, can be chosen to fully or partially imposed. Thereby, Eq. (3) should be satisfied. The strictest criterion that needs the largest required MCR to meet is selected based on the simulation results across different wave directions and periods.

$$(\bar{u} \geqslant u_{\min}) \text{ and/ or } \left(\left|\bar{\beta}\right| \leqslant \beta_{\max}\right) \text{ and/ or } \left(\left|\bar{\delta}\right| \leqslant \delta_{\max}\right) \tag{3}$$

Finally, the critical interval of MCR_{REQ} is found, where the corresponding measure values are above and below the threshold of the strictest criterion, respectively. The interpolated result within the MCR interval by using the threshold value of the strictest criterion is taken as the MCR_{REQ}.

3 Other assessment methods in IMO documents

Apart from the 3DOF TD method proposed in this study, three other assessment methods are considered for comparisons and analyses, i.e., the 3DOF SE method based on the IMO draft document[3], the 1DOF SE method and the MPL method derived from the current MPP guidelines[2]. It should be pointed out that the 1DOF and 3DOF SE methods are named by the authors to align with the 3DOF TD method for clearer representation and distinction, rather than the formal wordings utilized in the IMO documents.

3DOF SE method: The 3DOF steady-state equilibrium equations utilized in this study, i.e. Eqs.(4a)-(4c), are simplified from the established time-domain mathematical model, where all the terms related to acceleration and yaw rate are equal to zero.

$$X_{\mathrm{H}} + X_{\mathrm{W}} + X_{\mathrm{A}} + X_{\mathrm{R}} + X_{\mathrm{P}} = 0 \tag{4a}$$

$$Y_{\mathrm{H}} + Y_{\mathrm{W}} + Y_{\mathrm{A}} + Y_{\mathrm{R}} = 0 \tag{4b}$$

$$N_{\mathrm{H}} + N_{\mathrm{W}} + N_{\mathrm{A}} + N_{\mathrm{R}} = 0 \tag{4c}$$

The calculation methods of all the above items are consistent with the time-domain method, except that the drift force and moment are calculated by directly using spectrum method. The required forward speed $u_{\min}$ is directly input in advance, opposite to the time-domain method. The required drift angles $\tilde{\beta}$, rudder angles $\tilde{\delta}$, and propeller thrusts $\tilde{X}_{\mathrm{P}}$ can be solved from the equations. It should be noted that ψ is not a related variable here and is therefore assumed to be zero. Thereupon, the utilization of time- and heading-angle-dependent autopilot and guidance systems is deemed unnecessary and impractical. As a result, the course-keeping ability criteria cannot be considered as reasonable constraints in this method. When carrying out MPP assessment, $\tilde{\beta}$, $\tilde{\delta}$, and $\tilde{X}_{\mathrm{P}}$ are solved by solving Eqs.(4a)~(4c) over the specified wave directions and periods. The required rotation rates $\tilde{n}_{\mathrm{REQ}}$ and brake powers $\tilde{P}_{\mathrm{REQ}}$ can be determined at the same time. Then, a certain torque/speed limit of engine with a preset n_{MCR} is assumed to pass exactly through the maximum operational point ($\tilde{n}_{\mathrm{REQ}}$, $\tilde{P}_{\mathrm{REQ}}$) among the calculated wave directions and periods. Finally, MCR_{REQ} can be calculated by the torque/speed limit.

1DOF SE method: The longitudinal steady-state equilibrium Eq. (5) at the speed of $u_{\min}$ has been provided in the MPP guidelines, where R represents the calm-water resistance.

$$R + X_{\mathrm{A}} + X_{\mathrm{W}} + X_{\mathrm{R}} + X_{\mathrm{P}}(1 - t_{\mathrm{P}}) = 0 \tag{5}$$

The calculation methods of related terms are as consistent with the MPP guidelines as possible, which are different from the 3DOF TD method and 3DOF SE method. The required propeller thrust $\tilde{X}_{\mathrm{P}}$ (also the corresponding $\tilde{n}_{\mathrm{REQ}}$ and $\tilde{P}_{\mathrm{REQ}}$) is solved out by Eq. (5). Similarly, MCR_{REQ} is further computed according to the exactly satisfied OLE, as described earlier.

MPL method: This method does not solve for any specific manoeuvring motion. The power line provides the lower limit of the required installed power, based on the statistical data of existing ships. Accordingly, MCR_{REQ} can be calculated by Eq. (6).

$$MCR_{\mathrm{REQ}} = a \cdot DWT + b \tag{6}$$

where the coefficients a and b for different ship types can be found in the MPP guidelines.

In summary of Chapters 2 and 3, the frameworks and procedures of the four methods presented are depicted in Fig. 5 for a better illustration. These methods correspond to three levels of different complexity (i.e., level-1 empirical, level-2 simplified, and level-3 comprehensive, respectively). It is worth mentioning that this study presents direct calculation procedures for MCR_{REQ} in all the methods above, rather than checking

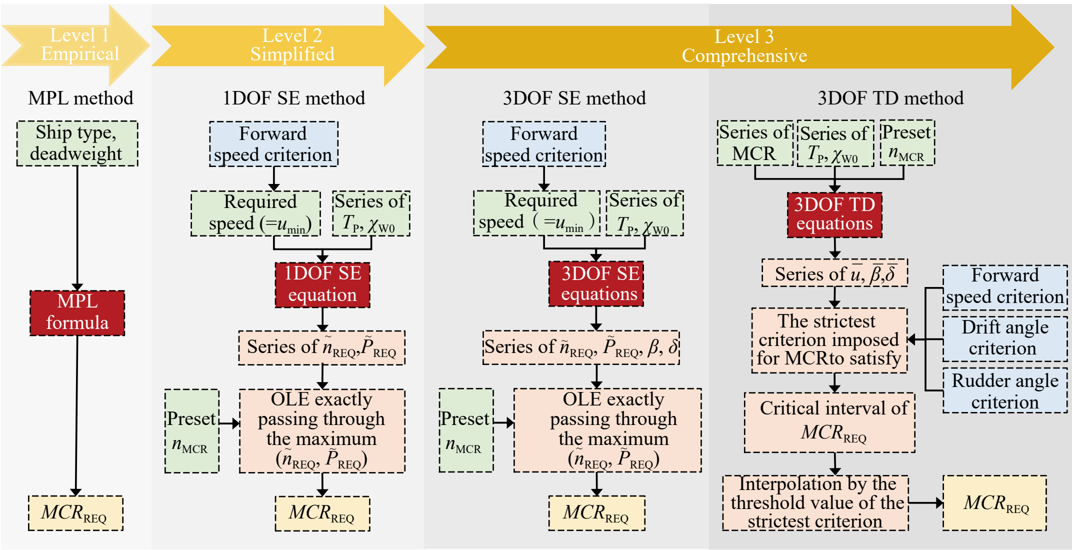


Fig.5 Multi-level frameworks and procedures of four MPP assessment methods

whether the required power would exceed the OLE or minimum power line for an existing installed engine as the IMO guidelines and documents do. It is valuable for the initial design and engine selection of a new ship. In addition, it should be noted that the variation of n_{MCR} will also impact the assessment results (except the level 1). Hence, multiple values of n_{MCR} can be employed as reference for the final MPP determination.

4 Assessment results and discussions

4.1 Assessment results

According to the definition in the revised guidelines, the adverse conditions corresponding to KVLCC2 are set as H_{S} = 6.0 m and U_{A0} = 22.6 m/s. The JONSWAP (Joint North Sea Wave Project) wave spectrum is employed. As a sophisticated and comprehensive problem, MPP assessment involves several significant influence factors at the aspect of criterion condition and calculation parameters. Six factors with different selected values are employed, as outlined in Tab.3, where the conditions specified in the revised guidelines are highlighted in bold and "N.R." represents "Not Required" in the assessment.

Tab.3 Influence factors and selected values

Influence factor	Selected values	Influence factor	Selected values
Minimum forward speed criterion	**2 kn**, 4 kn, 6 kn	Range of wave direction	180° only, **180°–150°**, 180°–135°
Maximum drift angle criterion	**N.R.**, 20°, 10°	Self-propulsion factors	ω_{P}= 0.35, 0.21, **0.15** t_{P}= 0.22, 0.15, **0.10**
Maximum rudder angle criterion	**N.R.** (= δ_{lim}), 25°, 20°	Control strategy	Refer to Tab.4

Tab.4 Considered guidance and autopilot (only for the time-domain method)

Case	P	PID	P+LOS
Autopilot parameters	k_{P} =2, k_{I} =k_{D} =0	k_{P} =2, k_{I} =0.01, k_{D} =20	k_{P} =2, k_{I} = k_{D} =0
Guidance	×	×	√

Firstly, the MPP assessment is conducted by using different methods under the specified condition of the revised guidelines, with the results displayed in Tab. 5. Subsequently, the results accounting for various influence factor values as well as employing different assessment methods are provided, as depicted in Figs. 6–9. It should be noted that MPL method is exclusively applied within the specified forward speed and

Tab.5 Assessment results employing different methods under the specified condition of MPP guidelines ($u_{\min}$ = 2 kn, $\beta_{\max}$ N.R., $\delta_{\max}$ N.R., χ_{W0} = 180°–150°, ω_{P} = 0.15, t_{P} = 0.10, P control)

Method (level)	MPL (Lv.1)	1DOF SE (Lv.2)	3DOF SE (Lv.3)	3DOF TD (Lv.3)
MCR_{REQ} /kW	25 668	24 866	23 783	23 599

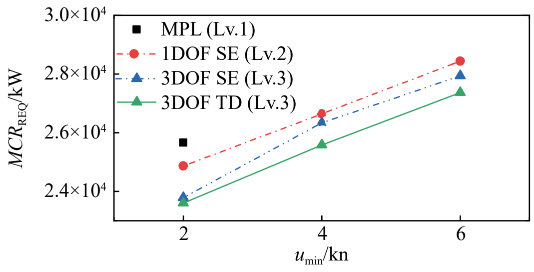


Fig.6 Assessment results employing different forward speed criteria by using different assessment methods ($\beta_{\max}$ N.R., $\delta_{\max}$ N.R., χ_{W0} =180°–150°, ω_{P} =0.15, t_{P} =0.10, P control)

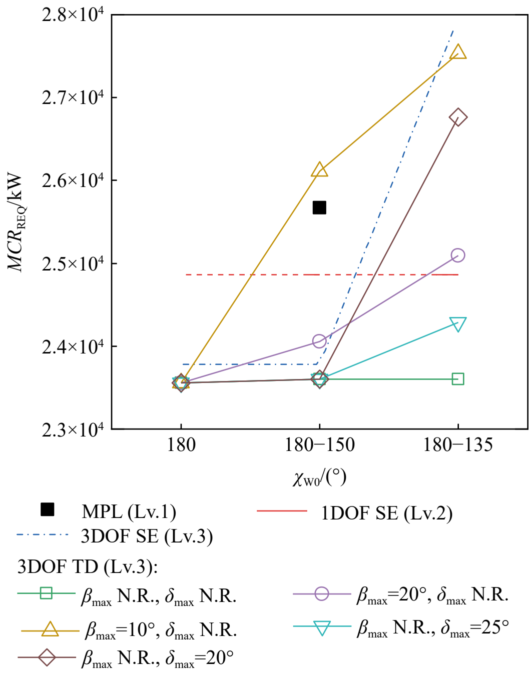


Fig.7 Assessment results employing different wave direction ranges by using different methods and criteria ($u_{\min} = 2$ kn, $\omega_P = 0.15$, $t_P = 0.10$, P control)

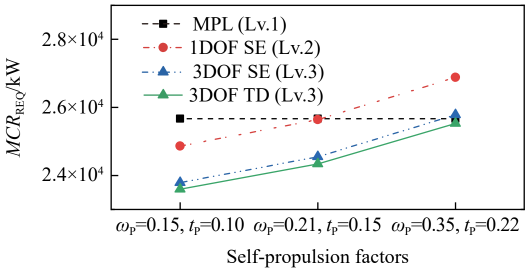


Fig.8 Assessment results employing different self-propulsion factors by using different assessment methods ($u_{\min} = 2$ kn, $\beta_{\max}$ N.R, $\delta_{\max}$ N.R., $\chi_{W0} = 180°–150°$, P control)

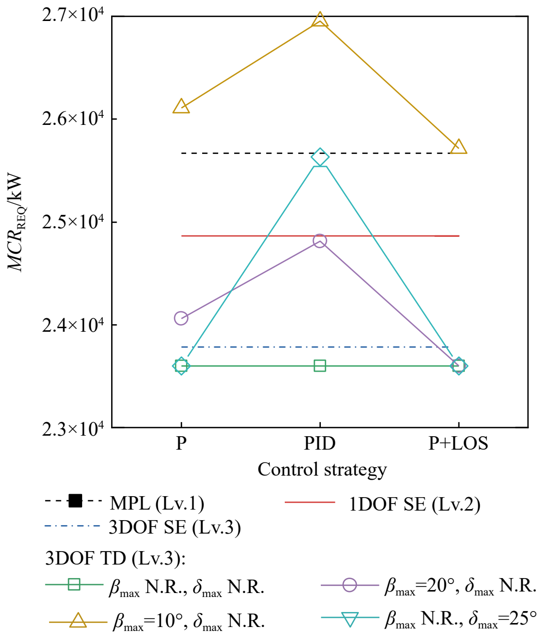


Fig.9 Assessment results employing different control strategies by using different methods and criteria ($u_{\min} = 2$ kn, $\chi_{W0} = 180°–150°$)

wave direction range in the MPP guidelines. The corresponding analyses and discussions are elaborated in the following sections.

4.2 Discussions on assessment methods

As indicated in Tab. 5, when the assessment condition is in agreement with the guidelines, the assessment results decrease from level-1 to level-3, also falling down from steady-state methods to time-domain method. It is generally accepted and rational that a more advanced and comprehensive method should give more accurate and less conservative results. In the meantime, the disparity in the calculation results between the 3DOF TD method and the 3DOF SE method is almost negligible. This can be attributed to the fact that only the speed criterion is considered. Besides, the influence of dynamic manoeuvres on forward speed, as considered by the time-domain method, is relatively insignificant in this case. Consequently, the accuracy of the 3DOF SE method proves to be satisfactory for KVLCC2 under this condition.

However, a contrast can be observed in Figs. 6–9 that there are notable differences between the results obtained from the time-domain method and other methods when the course-keeping ability criteria are imposed. On one hand, the course-keeping ability criteria are exclusively applied in time-domain assessment, and they do not introduce any influence for the steady-state methods. The MPL value in level-1 assessment reflects the overall performance of a given ship, and thus it keeps constant even when other variables change. On the other hand, the 3DOF SE method incorporates the effect of lateral force and yaw moment to yield more accurate results, but the calculated drift and rudder angles are on the basis of a fixed heading and unrealistic steering. While the 3DOF TD method takes a better account of the actual heading deflection and steering control, and the assessment results contain the stricter requirement of course-keeping ability. These reasons lead to the differences in the assessment results.

In brief, the MPL method and the 1DOF SE method are adopted in the MPP guidelines, offering convenient ways for engineering applications without complicated calculations and analyses. However, the applicability of the MPL simple formula may be limited for certain ships, and the simplified longitudinal equation does not fully address the original intention of MPP assessment, particularly with regard to the course-keeping ability. The more complex 3DOF SE method enhances the accuracy of the 1DOF steady-state equation while maintaining computational efficiency superior to that of the time-domain method. Nonetheless, the course-keeping ability criteria are unsuitable to impose as well. The most sophisticated 3DOF TD method provides a more precise description of actual manoeuvre behaviors, and yields more accurate and comprehensive assessment results. Correspondingly, it brings about larger uncertainty with more necessary input parameters, which reduces its practicality, especially when implemented as a regulation. Notwithstanding, it offers a feasible solution for the ships that cannot meet the requirements in other assessment levels, or those with unconventional design and equipment, or with the consideration of course-keeping requirement. In general, different methods exhibit varying complexity and advantages, together forming a multi-level assessment framework for MPP. They should be allowed for free selection according to the specific stage and corresponding need.

4.3 Discussions on influence factors

Propulsion ability criterion: In the interim guidelines, the minimum forward speed $u_{\min}$ was set as 4–9 kn, depending on the windage area and rudder area. However, in the revised guidelines, $u_{\min}$ is reduced to 2 kn and not directly relevant to hull form, rudder design, and course-keeping ability. Meanwhile, it has been pointed out by IMO Correspondence Group[16] that 2 kn is not the consensus, and it could be further strengthened (e.g., 4 kn) for future discussion. Fig. 6 shows that, if $u_{\min}$ is increased to 4 kn or 6 kn, the MCR_{REQ} values of level-2 and level-3 assessments rise significantly, resulting in more stringent requirement to the installed power.

Course-keeping ability criteria & wave direction range: The required range of wave direction in the revised guidelines has been expanded from only head seas (χ_{W0} = 180°) at first to 30° off-bow (χ_{W0} = 150°) now. It can be noticed that the interim guidelines previously proposed requirements for keeping course in all wave directions. Therefore, it remains to be discussed whether further expansion of the range is necessary to consider the possible impact. Fig. 7 firstly presents that the level-2 and level-3 assessment results for χ_{W0} = 180°–150° without course-keeping criteria are nearly identical to those obtained when considering χ_{W0} = 180° only. This is because MCR_{REQ} reaches the maximum value near the wave direction of χ_{W0} = 180° in short-crested waves. (However, MCR_{REQ} will have a significant increase if long-crested waves are considered, due to the larger added resistance in bow waves rather than head waves.) Secondly, since the lateral drift force and yaw moment lead to a significant drift angle in the 30°–45° off-bow waves, MCR_{REQ} goes up with the additional consideration of maximum drift angle criterion. A dramatic increase occurs under the criterion of $\beta_{\max}$ = 10°, while $\beta_{\max}$ = 20° seems relatively reasonable and acceptable to some extent, as it can improve course-keeping ability in severe sea conditions while can not considerably increase MCR_{REQ}. Thirdly, if the range is expanded to 45° off-bow, it places notable demand on course-keeping ability, and the restriction of δ_{max} criterion on MPP starts to become apparent in this situation. Lastly, the criteria of $\beta_{\max}$ = 20° and $\beta_{\max}$ = 10° appear stricter for MPP assessment than the criteria of $\delta_{\max}$ = 25° and $\delta_{\max}$ = 20°.

Self-propulsion factors: The recommended self-propulsion factors in the interim guidelines are estimated at design speed, and the revised guidelines adopt the default values that were reported through a number of model tests at low speeds. The results in Fig. 8 depict obvious discrepancy when different self-propulsion factor values are applied. The self-propulsion factors at design speed lead to larger required thrust and power. It seems unnecessary for the assessment results to be overly conservative due to inappropriate self-propulsion factors. However, the 30 th ITTC[17] has newly pointed out that the power predictions based on the default values may be not necessarily conservative for a full-block ship. The selected values at low speeds, especially at $u_{\min}$, are much crucial for MPP assessment but still remain disputed at present. Furthermore, the variation of self-propulsion factors in waves has not been taken into account in current guidelines, and further study on its impact should be carried out by using time-domain method.

Rudder control strategy: It should be pointed out that autopilot is usually taken over by manual operations under extreme sea conditions, but it is also of significance to employ reasonable guidance and autopilot to approximately simulate the manoeuvring motion for a time-domain comprehensive assessment. As shown in Fig. 9, the different control strategies have no clear impact on the results when course-keeping ability criteria are not imposed. While the $\beta_{\max}$ criterion is considered, different control strategies result in different MCR_{REQ}, especially with different autopilots. Moreover, the assessment under $\delta_{\max}$ criterion mainly depends on the autopilot and exhibits a weak correlation with the application of guidance. These results also highlight a challenge in conducting time-domain assessment, specifically in how to account for the rudder control closer to real operations at seas.

5 Conclusions

The following conclusions can be drawn:

(1) The MPL method and 1DOF SE method adopted in IMO guidelines are convenient for engineering applications with fewer input parameters. The 3DOF SE method based on the draft document of MPP guidelines relatively enhances the accuracy of calculating steady-state motion. While the 3DOF TD method proposed in this study offers a more sophisticated approach for achieving more accurate and comprehensive assessment. Overall, diverse methods can effectively fulfil their respective roles when targeted at different needs, and collectively establish a multi-level assessment framework system for MPP assessment.

(2) It is recommended to enhance the MPP guidelines by incorporating criteria and measures related to course-keeping ability, such as drift angle and rudder angle. This will contribute to better assessing the manoeuvrability of ships in severe sea conditions and ensure navigation safety. Additionally, it is suggested to consider permitting the time-domain comprehensive assessment as an optional choice. This approach could offer a viable solution for the ships that do not meet other assessment levels, as well as for situations where course-keeping ability assessment is required.

(3) The drift angle and rudder angle criteria in course-keeping ability set stricter demands on MPP compared to the forward speed criterion, and the requirements such as $\beta_{\max} = 20°$ and $\delta_{\max} = 25°$ seem relatively reasonable and acceptable. When a wider range of wind and wave direction is considered, the drift effect is more intense and leads to a more conservative result. Meanwhile, the self-propulsion factors at low speeds eliminate the unnecessary conservation of the required power caused by those at design speed. In addition, the rudder control strategy employed in time-domain assessment makes a significant difference on the fulfilment of course-keeping ability criteria.

MPP assessment in adverse conditions poses a complex challenge. Future efforts should focus on further enhancing hydrodynamic and engine mathematical models, expanding assessment cases for different hull forms and smaller vessels, and developing comprehensive methods that align with both EEDI and MPP regulations to resolve the intrinsic conflict between manoeuvrability safety and energy efficiency.

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船舶最小推进功率评估方法及影响因素探讨

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摘要：当前，国际海事组织批准施行了船舶在恶劣海况中最小推进功率的评估要求，而其评估方法和相关影响因素将会对船舶设计和运营产生至关重要影响。另一方面，最小功率评估本质上是实海域操纵安全衡准问题。然而，现行导则中的评估方法尚未直接和准确地考虑恶劣海况中船舶的航向保持能力。作者在前期研究中提出了一种时域综合评估方法，在增加航向保持能力衡准后提供更为全面的评估。本文基于新数学模型和衡准准则针对该时域方法进行了更为详尽的阐述、结果展示和讨论，其中包括了该方法与基于导则/草案的最小功率线法及两种稳态平衡方法的比较分析，以及对于衡准条件和计算参数等关键影响因素的探讨。结果表明，不同方法在评估中表现出不同的优势和复杂度，共同形成了一种多层次的最小推进功率评估框架。其中，时域综合评估因能更准确地描述真实操纵运动而具有更高精度，同时可为无法满足其他评估要求或是补充航向保持能力评估的船舶提供解决方案。此外，扩大评估浪向范围提出了更为严格但可能必要的要求，而使用低航速自航因子可消除采用设计航速值时带来的不必要的保守度。

关键词：实海域操纵性；最小推进功率；综合评估；操纵性衡准；航向保持
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