Navigability assessment of ships in ice using ice chart information

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ABSTRACT

Arctic sea ice has been decreasing rapidly. However, sea ice is still a serious hazard for arctic navigation, especially for a large merchant vessel with low ice class. The authors developed the method for predicting ship resistance and propulsion power in an ice regime using ice chart information. Based on these methodologies, the authors propose a method for evaluating propulsion-performance limits in an ice regime. The procedure of propulsion-performance limit assessment is demonstrated for an ice-strengthened merchant vessel. The navigability limit of vessels in ice waters can be evaluated from two perspectives: structural safety, which is determined by the strength of the hull and propulsion system, and propulsion performance, which is determined by the hull form and the output of the propulsion system. AIRSS for the Canadian Arctic and POLARIS for the Arctic Ocean are the systems that evaluate navigational risks and provide safety limit for ships navigating in ice using ice chart information. Toward realizing more comprehensive assessment of ice navigability, the authors proposed the framework of the navigability assessment of ice-class vessels by combining POLARIS with the proposed method for evaluating propulsion-performance limits in an ice regime.

KEY WORDS

Navigability assessment; POLARIS; Propulsion-performance limit, Ice chart.

INTRODUCTION

Arctic sea ice has been decreasing rapidly. However, sea ice is still a serious hazard for arctic navigation, especially for a large merchant vessel with low ice class. A lot of research have been conducted toward safe and efficient ice navigation. In these studies, ice information is mainly derived from satellite remote sensing or simulation.

An ice chart is one of the data sources of sea ice conditions, incorporating an ice regime, a specific area of ice waters with relatively uniform ice conditions, and a WMO egg code that expresses the ice conditions in an ice regime. Yamauchi et al. (2018) estimated the ship performance for navigation through NSR by coupling analytical modeling of ship ice performance and the information of a WMO egg code in an ice chart. However, the detail of the derivation is not given in their paper. Frederking (2003) developed a model for determining transit times and fuel consumption for ships transiting through ice-covered waters using ice chart information. In his study, the effective ice thickness was determined from the category of the stage of development in a WMO egg code.

The authors developed the method for predicting ship resistance and propeller thrust in an ice regime using WMO egg code information (Uto. 2021, Uto and Toyota, 2022). The authors extend this method and propose a simple method for estimating the propulsion power of ships in an ice regime (Uto and Matsuzawa, 2023). In this paper, the authors describe the outline of the resistance and propulsion-performance estimation procedures using ice chart information, emphasizing its application for a large merchant vessel navigating in moderate ice. Based on these methodologies, the authors further propose a method for evaluating propulsion-performance limits in an ice regime using ice chart information.

The navigability limit of ships in ice waters can be evaluated from two perspectives: structural safety, which is determined by the strength of the hull and propulsion system, and propulsion performance, which is determined by the hull form and the output of the propulsion system. AIRSS for the Canadian Arctic (Transport Canada, 2017) and POLARIS for the Arctic Ocean (IMO, 2016) are the systems that evaluate navigational risks and provide navigability limits related to structural safety using ice chart information.

It is obvious that AIRSS or POLARIS does not guarantee ice navigation from a propulsion-performance point of view. It means that there may be cases where navigation is not possible due to propulsion performance even if normal operation is allowed by POLARIS. Toward realizing more comprehensive assessment of ice navigability, the authors propose a framework of the navigability assessment of ice-class vessels navigating independently by combining POLARS with the proposed method for evaluating propulsion-performance limits in an ice regime.

METHODS

Evaluation of resistance increase in an ice regime using ice chart information

Uto and Toyota (2022) proposed the formulation for the resistance prediction scheme of ships in an ice regime using ice chart information.

In an ice chart, sea ice conditions in an ice regime are described by a WMO egg code, which includes total and up to three partial concentrations (*C*), a stage of development (*S*), and a form of ice (*F*) for each partial concentration. It is assumed that an ice regime consists of up to three sub-ice regimes and each sub-regime exists independently. Figure 1 shows the image describing how to decompose one ice regime to three sub-ice regimes.

A stage of development and a form of ice is described by not a digit, but by a category defined by the WMO Sea Ice Nomenclature. The method to derive representative ice thickness from the category of a stage of development was proposed in the previous studies (Frederking, 2003, Izumiyama and Otsuka, 2013, Milaković et al., 2018). Basically, the same method is adopted in the present study. Representative floe size is derived from the category of a form of ice by considering its self-similarity nature (Uto, 2021).

These values as well as partial ice concentration are substituted to the analytical model to predict ice resistance (denoted as resistance increase due to ice) in each sub-ice regime. The model consists of two analytical models, i.e., the resistance prediction model in a large ice floe by Lindqvist (1989) and that in small ice floes by Kashteljan, Poznjok and Ryblin (denoted as the KPR model, Nozawa, 2006). Resistance increase in each sub-ice regime is determined as the lower value of those calculated by the two models (Uto et al., 2015).

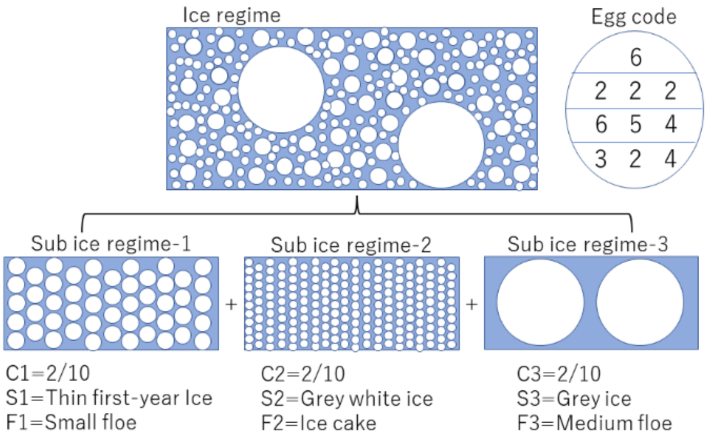


Figure 1. Image of an ice regime and three sub-ice regimes

Assuming the encounter frequency for ships is determined by its partial concentration (C_i) divided by the total concentration (C_T), the mean resistance increase due to ice in an ice regime is calculated by equation (1).

$$\Delta R_I = \frac{1}{C_T} \sum C_i \Delta R_{subi}(C_i, S_i, F_i) \tag{1}$$

Here ΔR_{subi} is resistance increase in the sub-ice regime-i.

Uto and Toyota (2022) conducted the validation study of the proposed method by comparing the results of the shaft output measurements on board the patrol vessel, icebreaker SOYA in the marginal ice zone in the south Okhotsk Sea. During the shaft output measurements, the experts conducted shipborne visual observations and collected sea ice data corresponding to WMO egg code. An area of 1km in radius in visual observations is assumed to be an ice regime and the results are used as input of the resistance formulae in an ice regime. It was reported that good agreement was obtained between measured and predicted thrust, showing the validity of the present resistance formulae in an ice regime in the marginal ice zone in the south Okhotsk Sea.

Evaluation of required power in an ice regime

Uto and Matsuzawa (2023) proposed the formulation of the powering procedure by referring to the recommended procedures and guidelines on “Preparation, Conduct, and Analysis of Speed/Power Trials” published by International Towing Tank Conference (ITTC, 2022).

It is assumed that the power in ice (P) is decomposed into the power in ice-free water (P_W), and power increase due to ice (ΔP_I).

$$P = P_W + \Delta P_I \tag{2}$$

ΔP_I is derived by equation (3) by assuming it is small compared to P_W.

$$\Delta P_I = \frac{V_S \Delta R_I}{\eta_W} + P_W (1 - \frac{\eta_I}{\eta_W}) \tag{3}$$

This is one of the most important assumptions and regarded to be valid at least if a large merchant vessel navigates in moderate ice condition.

Here, V_S is ship speed. η_I and η_W are propulsive efficiency coefficients in ice and ice-free water, respectively.

$$\eta_I = \eta_{OI} \eta_{RI} \frac{1 - t_I}{1 - w_{SI}} \tag{4}$$

$$\eta_W = \eta_{OW} \eta_{RW} \frac{1 - t_W}{1 - w_{SW}} \tag{5}$$

Here, η_O is a propeller open water efficiency. t is a thrust deduction factor. w_S is a full-scale wake fraction. η_R is a relative rotative efficiency.

As a prerequisite, the results of power estimation in ice-free water as well as that of the propeller open characteristics are to be given. It is further assumed that t, w_S, and η_R in ice are the same as those in ice-free water.

Thus, a propulsive efficiency coefficient in ice is obtained by equation (6).

$$\eta_I = \eta_{OI} \eta_{RW} \frac{1 - t_W}{1 - w_{SW}} \tag{6}$$

From the results of a propeller open test, thrust coefficient (K_T), torque coefficient(K_Q),and load factor (τ_P),can be written from equations (7) to (9).

$$K_T = a_T J^2 + b_T J + c_T \tag{7}$$

$$K_Q = a_Q J^2 + b_Q J + c_Q \tag{8}$$

$$\tau_P = a_T + b_T \frac{1}{J} + c_T \frac{1}{J^2} \tag{9}$$

Here,

$$K_T = \frac{T}{\rho n^2 D^4},\ K_Q = \frac{Q}{\rho n^2 D^5},\ \tau_P = \frac{K_T}{J^2},\ J = \frac{V_A}{nD}$$

n is a propeller revolution speed. D is a propeller diameter. V_A is an advance speed of a propeller in uniform flow.

At each ΔR_I and V_S, η_{OI} and n_I are obtained by equations (10) and (11), respectively.

$$\eta_{OI} = \frac{J_I}{2\pi} \frac{K_{TI}}{K_{QI}} \tag{10}$$

$$n_I = \frac{V_S (1 - w_{SW})}{J_I D} \tag{11}$$

Here,

$$K_{TI} = a_T J_I^2 + b_T J_I + c_T \tag{12}$$

$$K_{QI} = a_Q J_I^2 + b_Q J_I + c_Q \tag{13}$$

$$J_I = \frac{-b_T - \sqrt{b_T^2 - 4(a_T - \tau_{PI})c_T}}{2(a_T - \tau_{PI})} \tag{14}$$

$$\tau_{PI} = \frac{R_W + \Delta R_I}{(1-t_W)(1-w_{SW})^2 \rho_S V_S^2 D^2} \tag{15}$$

Finally, the power in ice is estimated through equations (2), (3), (6), and (10).

The accuracy of this method was verified using the results of the shaft output measurements on board the patrol vessel, icebreaker SOYA in the marginal ice zone in the south Okhotsk Sea (Uto and Matsuzawa, 2023). Table 1 shows the principal dimensions of P/V SOYA. Again, the onboard visual observations of sea ice were used for characterizing ice regimes. Table 2 lists the ice conditions of three ice regimes. The ice thickness and floe size in each ice regime are converted to representative values.

Table 1. Principal dimensions of P/V SOYA

		Unit
Length overall	98.6	m
Length waterline	90.0	m
Breadth molded	15.6	m
Dept molded	8.0	m
Draft	5.2	m

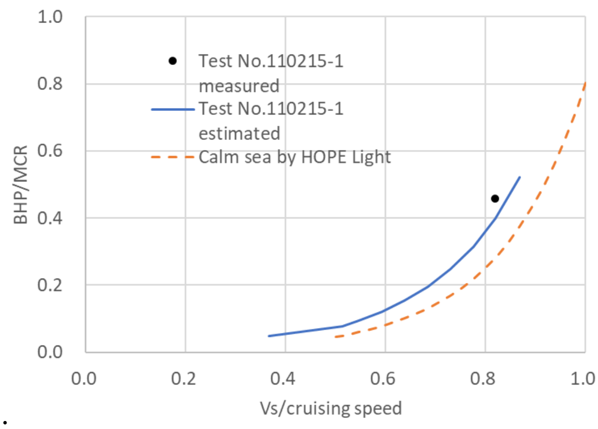
Table 2. Results of onboard sea ice observation of three ice regimes

Ice Regime	Total conc.	Sub regime	Conc.	Stage development	Rep.thick [m]	Ice type	Rep.size [m]
1	7	1-1	1	Thin FY	0.500	Brash	1.0
		1-2	6	Grease	0.010	-	39.6 *
2	10	2-1	8	Thin FY	0.500	Cake ice	4.8
		2-2	2	Brash	0.150	Brash	1.0
3	10	3-1	4	Thin FY	0.500	Small floe	39.6
		3-2	3	Thin FY	0.500	Cake ice	4.8
		3-3	3	Brash	0.150	Brash	1.0

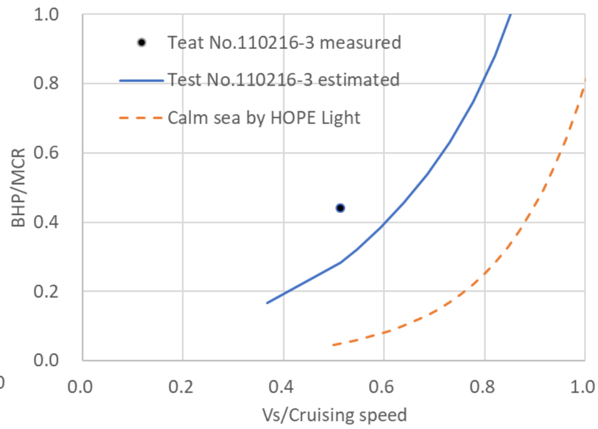
* Ice type of sub-regime 1-2 is assumed as a small floe.

Here, the results of resistance and power estimation in ice-free water as well as that of the propeller open test are obtained by HOPE Light, the ship performance estimation program developed by the National Maritime Research Institute (Ichinose and Kume, 2016). This program is capable of estimating ship performance in ice-free water by specifying a ship-type and principal particulars without detailed information on hull and propeller configurations.

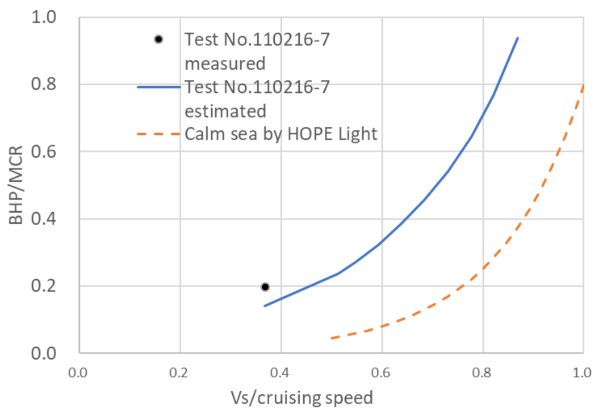
Figure 2 shows the comparison of the power curve in ice between measurement and prediction. Here, the propulsion power (*BHP*) and ship speed (V_S) are normalized by the maximum continuous output (*MCR*) of the main engine and the cruising speed, respectively. The power curve in ice-free water by HOPE-Light is plotted for reference. The estimated power is slightly underestimated but in good agreement with the measured results except for the case in Fig.2 (b).



(a) Ice regime-1



(b) Ice regime-2



(c) Ice regime-3

Figure 2. Comparisons of power curve in ice between measurement and prediction replotted from Uto and Matsuzawa (2023)

ASSESSMENT OF PROPULSION-PERFORMANCE LIMIT

A power curve gives maximum ship speed (V_S) attainable against the main engine's Maximum Continuous Rating (*MCR*). Figure 3 illustrates the image of propulsion-performance assessment using a power curve for each ice regime.

As an example, the procedure of propulsion-performance assessment is demonstrated for an ice-strengthened merchant vessel. The vessel used for the analysis is the Panamax bulk career with ice class PC7. Table 3 shows the dimensions of the vessel. Its service speed and *MCR* (Maximum Continuous Rating of a main engine) are predicted as 14.5 knots and 11,513kW, respectively. It is assumed that the vessel navigates in three ice regimes listed in Table 2.

POLARIS gives the positive RIOs in three ice regimes and allows normal operation.

Figure 4 shows the power curve of the Panamax bulk career in three ice regimes. The power curve in ice-free water is obtained by HOPE Light and plotted in Figure 4 for reference. It should be noticed that the vessel has no icebreaking bow and resistance increase due to ice is determined by the KPR model, which is applicable to navigation in small ice floes.

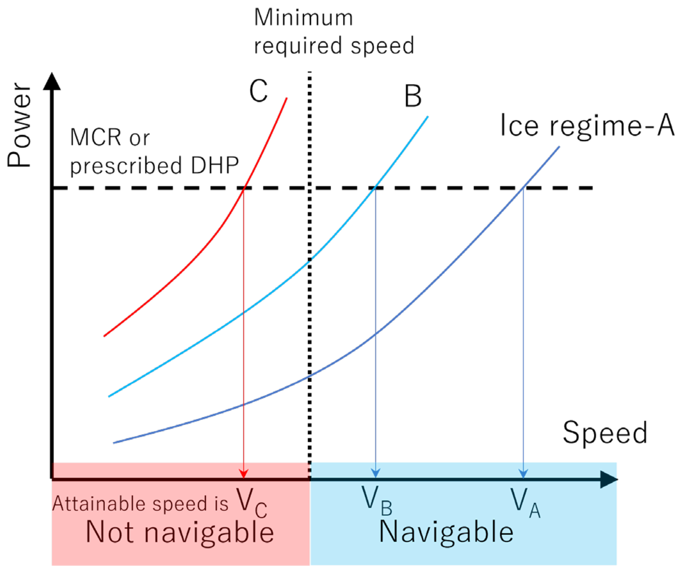


Figure 3. Image of the propulsion-performance assessment using a power curve for each ice regime

Table 3. Dimensions of Panamax Bulk Career

Dimension		
ShipName	Sample	
Loa	234.34	[m]
Lwl	228.16	[m]
Lpp	225.00	[m]
B	32.26	[m]
D	20.00	[m]
d	12.20	[m]
Cb	0.862	
Cm	0.996	
Cp	0.866	
Cpf	0.939	
Cpa	0.792	
Lcb(aft.+)	-3.49	[%Lpp]
Displ.	78270	[ton]
Dead Weight	66019	[ton]
M/E	S50ME-C8.2	
M/E MAKER	Mitsui	
Pro. Dia[m]	6.13	[m]
Service Speed	14.50	[knot]

The attained ship speed, defined by the cross point of each power curve against *MCR*, is evaluated at about 15 knots (regime-1), 11.3 knots (regime-2), and 12.5 knots (regime-3). It indicates that the vessel can navigate in moderate ice conditions independently at a speed of greater than 11 knots.

Even if the floe size of sub-regime 2-1 changes from ice cake to small ice floe (the representative size of 39.6m) and other parameters are unchanged (denoted as ice regime 2b), the RIO is positive and normal operation is allowed by POLARIS. However, the required power increases drastically, indicating the vessel has difficulty in independent navigation in such severer ice from the propulsion performance point of view (as shown in Figure 5).

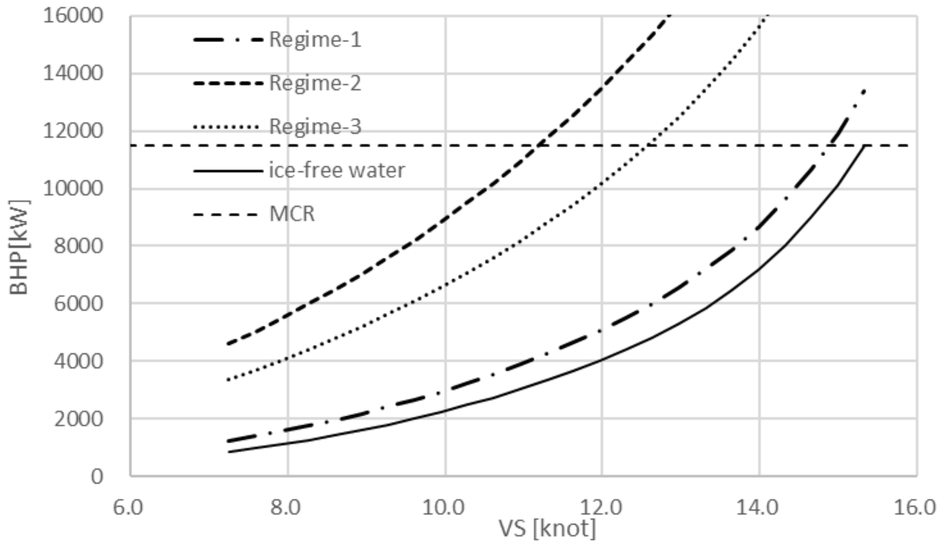


Figure 4. Power curve of Panamax bulk career in three ice regimes and ice-free water

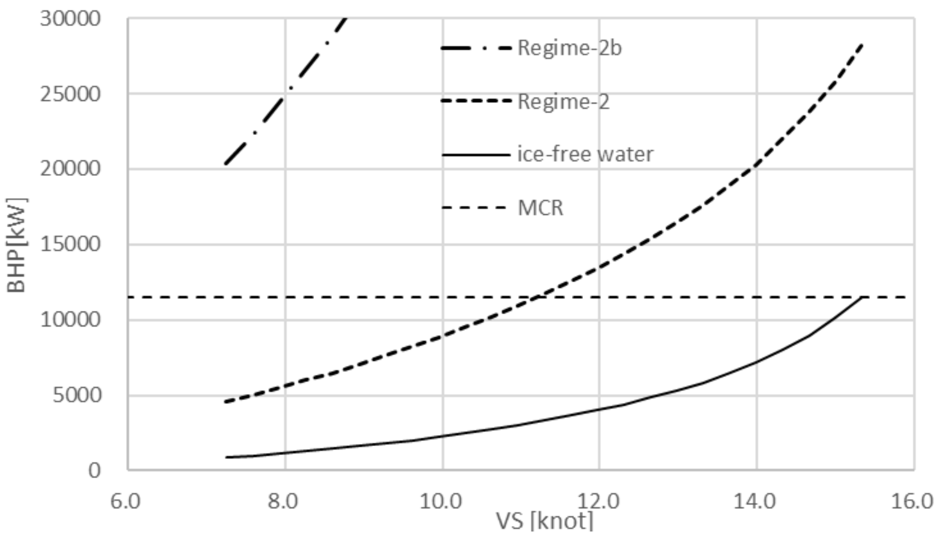


Figure 5. Power curve of Panamax bulk career in ice regime-2 with different floe size

FRAMEWORK OF NAVIGABILITY ASSESSMENT

The navigability limit of vessels in ice waters can be evaluated from structural safety and propulsion performance. AIRSS for the Canadian Arctic and POLARIS for the Arctic Ocean are the systems that evaluate navigational risks and provide safety limit for ships navigating in ice. In POLARIS, a vessel can navigate in the ice regime if the calculated Risk Index Outcome (RIO) is larger than the prescribed value. However, it is obvious that it does not guarantee ice navigation from a propulsion-performance point of view. It means that there may be cases where navigation is not possible due to propulsion performance even if normal operation is allowed by POLARIS. Figure 7 shows a proposed framework of the navigability assessment of ice-class vessels navigating independently, by combining POLARS with the proposed method for evaluating propulsion-performance limits in an ice regime.

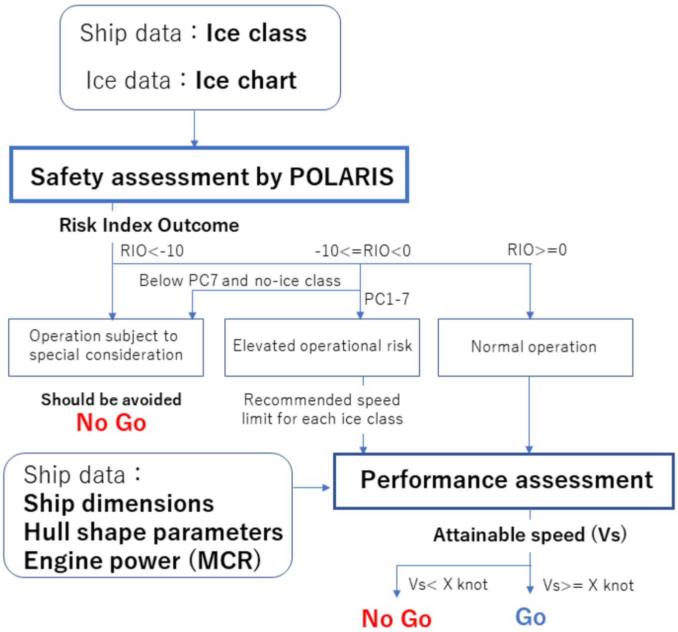


Figure 7. Framework of the navigability assessment in ice for ships of independent navigation

DISCUSSIONS

Propulsion-performance assessment requires an accurate evaluation of resistance increase due to ice in an ice regime. In the present study, the resistance increase of the Panamax bulk career is calculated by the KPR model, which considers the lateral displacement of small ice floes surrounding a vessel but no ice failure. However, the splitting failure mode could be a dominant mechanism in case of regime-2b in Figure 5, instead of the lateral displacement for a large ice floe, and consequently mitigate the resistance. Thus, it is probable that the estimated power for ice regime-2b is overestimated. The splitting mode should be included in the resistance prediction model in the future study.

The main challenges in power estimation for vessels in ice are overload conditions caused by interaction between ice and a hull, and the effects of interaction between a propeller and ice. The increase in power due to the interaction between a propeller and ice is mainly caused by increased torque due to contact between ice blocks and propeller blades. The changes in the propeller inflow field due to the flow of ice blocks around the hull may influence the power. However, these effects can be ignored when a large merchant vessel is navigating in moderate ice conditions.

The overload condition leads to an increase in the propeller load factor. The increase in propeller load factor changes the self-propulsion factors ($1\text{-}t$, $1\text{-}w$, η_R) and propeller open characteristics (η_o). In the present study, only changes in η_o are considered. The influence of the propeller load factor on the self-propulsion factors should be investigated in the future study (Adachi, 1983, Kume et al., 2021).

This method assumes that the power increase due to ice is small compared to the power in ice-free water. The previous study revealed that the estimated power in moderate ice conditions was slightly underestimated but in good agreement with the measured results except for the case with low speed (Uto and Matsuzawa, 2023). Further validation studies for various types of ships in various ice conditions are needed to investigate the applicability of the powering method, the method of the performance limit assessment, and a new framework of ice navigability assessment.

CONCLUSION

The authors developed the method for predicting ship resistance and propulsion power in an ice regime using WMO egg code information. In the present study, the authors further developed the method to evaluate the performance limit of ships in an ice regime. A predicted power curve of ships in an ice regime gives a performance limit, i.e., the attainable ship speed against the main engine's Maximum Continuous Rating (*MCR*). As an example, the procedure of performance limit assessment is demonstrated for an ice-strengthened merchant vessel (the Panamax Bulk Carrier). Toward realizing more comprehensive assessment of ice navigability, the author proposed the framework of the navigability assessment of ice-class vessels by combining POLARIS with the proposed method for evaluating propulsion-performance limits in an ice regime. Further validation studies for various types of ships in various ice conditions are needed to investigate the applicability of the powering method, the method of the performance limit assessment, and a new framework of ice navigability assessment.

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