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Fluid Force Modelling Affecting on Ice Piece for Ship Navigation in Broken Ice Fields

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ABSTRACT

Evaluating fluid forces on ice pieces accurately is important to improve the accuracy of simulations of ship navigation in broken ice fields. For this study, we introduced a better fluid force model for a simulator we have developed at Kogakuin University, Japan. This simulator implements physically based modelling to represent collision and friction of ice pieces and the ship hull. It can simulate ship navigation with more than 1 million broken ice pieces. The fluid force model implements the additional mass model with modification to stabilize the numerical simulation. The modified simulator was tested with ship navigation in brash ice channels. Its tendencies were compared with the resistance formula of Finnish–Swedish ice class rules (FSICR). Effects of treatment of acceleration of ice pieces and the factor of additional mass against the ship resistance are discussed.

KEY WORDS: Additional mass; Brash ice channel; Broken ice field; Numerical simulation; Physically based modelling

INTRODUCTION

When non-icebreaker ships navigate in icy oceans, they are often led by icebreakers depending on the ice conditions. Icebreakers break up the ice and clear a channel so that the following ships can navigate. At such times, the channel is filled with broken ice. As the ship navigates through the channel repeatedly, the ice piece sizes decrease. These ice pieces, which vary in size from about 2 meters in diameter or less, are called brash ice. Such a channel is therefore called a brash ice channel. For ships to navigate safely through brash ice channels, ascertaining how the ice pieces affect the ship is important. Normally, ships navigating in ice bound seas must meet the engine output, ice resistance and hull strength requirements of the Finnish–Swedish Ice Class Rules (FSICR, Finnish Transport Safety Agency, 2016). The FSICR resistance formula is often used to calculate the ship hull resistance. Model experiments in an ice tank test must be conducte to confirm the ship performance. However, conducting model experiments in an ice tank test is not easy because of the cost of model production, the cost of maintaining the ice tank, and the time necessary to cover the tank with ice. According to FSICR (3.2.5), "For an individual ship, in lieu of the K_e or R_{CH} values defined in 3.2.2 and 3.2.3, the use of K_e or R_{CH} values based on more precise calculations or values based on model tests might be approved." The FSICR allows the use of values from "more accurate calculations" or "model tests". It is therefore desirable to develop a ship navigation simulator that can evaluate the resistance to ship hulls more accurately.

A group at Kogakuin University has been developing a ship navigation simulator for situations in which many ice pieces surround the ship hull. Konno et al. (2013) simulated the experiment conducted by Wang et al. (2009) and demonstrated that the resistance can be predicted. However, earlier reports show that the relation between traction speed and resistance increases linearly in model experiments, whereas the analytical results show a quadratic increase. One reason for the difference between the analytical and experimentally obtained results is the treatment of fluid forces around the ice pieces. The equation used for analyses is an equation with a drag coefficient used when the flow is steady and there is only one object. However, ice pieces in actual ice bound sea exist in unsteady flow and the number of ice pieces is large. Therefore, accurately evaluating fluid forces around ice pieces is important. For this study, an added mass model is implemented into the existing fluid force model to evaluate the fluid force on ice pieces accurately. The analysis results are compared with those obtained with the FSICR resistance equation. Effects of treatments of ice piece acceleration and factors increasing the mass against ship hull resistance are also discussed.

METHODS

Physically Based Modeling

Ice piece motions such as collision and friction between ice pieces and a ship, and friction among ice pieces must be considered to evaluate resistance for ship navigation in a brash ice channel. To analyze ice motion, we are developing a simulation program that incorporates physically based modeling. Specifically, we use the Open Dynamics Engine (ODE, Smith, 2006): a physically based modeling library that is an open source physics calculation engine. The ODE library has functions such as friction and collision detection, calculation of interaction force, integration of equations of motion, and simple animation. We assume that the ice pieces are rigid bodies that are not mutually adherent, but subject to gravity and buoyancy as external forces.

In earlier studies by the authors' group (e.g., Konno et al. 2013), the fluid force on an ice piece is calculated using the formula shown in equation (1).

$$F_{Drag} = -C_D A \cdot \frac{1}{2}\rho\left|U_{ice} - U_{flow}\right|\left(U_{ice} - U_{flow}\right) \tag{1}$$

Therein, C_D is the drag coefficient, A expresses the projection area of the ice piece, ρ denotes the density of water, U_{ice} signifies the velocity of the ice piece, and U_{flow} is the velocity of the flow field. Equation (1) represents the force in steady flow field.

For this study, we replaced equation (1) with equation (2). Equation (2) is an added mass model adapted to account for acceleration resistance during accelerated motion of ice pieces.

$$F_{Mass} = -\rho C_a V_{ice} a_{ice} \tag{2}$$

Therein, ρ represents the water density, C_a is the added mass coefficient, V_{ice} denotes the volume of the submerging portion of the ice piece and a_{ice} stands for the ice piece acceleration. For this study, emphasis is put on the correct treatment of kinetic phenomena such as friction and collision of ice pieces. Therefore, we consider the added mass of each ice piece. The added mass coefficients in the x-direction (surge) and y-direction (sway) are assumed respectively as C_{a_x}=0.5 and C_{a_y}=0.5. The added mass coefficient in the z-direction (heave) is inferred as follows: (a) When the total volume of the ice piece is above the water surface, the added mass coefficient is set to 0. (b) C_{a_z} = 0.5 when the total volume of ice pieces is below the water surface. When the ice pieces contact each other or the hull, and when the ship descends during ascent or turns to ascent during descent, the velocity approaches 0 m/s. The velocity difference becomes small. Therefore, the added mass factor is set to 0. (c) When a part of the ice piece is out of the water surface, the added mass coefficient is set to zero when the movement of the ice piece reverses as in (b). Otherwise, it is given by a linear equation according to the ice piece height. Table 1 shows the added mass coefficients depending on the ice piece condition.

Table 1. Added mass coefficients depending on the ice piece condition

Situation		Added mass coefficient
(a) An ice piece is above the water surface.	Fluid force is negligible.	Ca_x=0.0, Ca_y=0.0, Ca_z=0.0
(b) An ice piece is under the water surface.	Direction of motion is reversed	Ca_x=0.5, Ca_y=0.5, Ca_z=0.0
	otherwise	Ca_x=0.5, Ca_y=0.5, Ca_z=0.5
(c) Part of an ice piece is above the water surface.	Direction of motion is reversed	Ca_x=0.5, Ca_y=0.5, Ca_z=0.0
	otherwise	Ca_x=0.5, Ca_y=0.5, 0<=Ca_z<=0.5 (depends linearly on the submerged height)

Simulation Conditions

We used the Japan Bulk Carrier (JBC) ship model for our simulation. The JBC was selected as a test case during "Tokyo 2015 A Workshop on CFD Ship Hydrodynamics (NMRI, 2015)". The geometry of JBC is shown in Figure 1. The model dimensions are presented in Table 2. The length between perpendiculars (L_{pp}) of the JBC is 280 m. The maximum beam of waterline (B_{wl}) is 45 m. For these analyses, we assumed the Panamax size for the ship. Therefore, we resized the JBC to make the ship width 32 m. In this case, the length becomes 199.11 m. The provided hull data from the Tokyo 2015 Workshop is a model of 7 m length and 1.125 m width. Because we use model data without rescaling, the scale ratio becomes 28.5. The model ship has neither a rudder nor a propeller.

The channel dimensions and initial arrangement of the ice pieces used in this simulation are shown in Figures 2 and 3. The channel length is 21.0 m (L_{pp}×3) to conform to Konno et al. (2009), the channel width is 2.25 m (B_{wl}×2). The channel thickness is 0.03515 m to conform the FSICR guideline (Swedish Transport Agency, 2018). The ice piece is a sphere. An actual ice piece of 50 cm was assumed. Therefore, the ice piece diameter was created to be normally distributed at 0.017578 m. The ice pieces were arranged irregularly and in two layers. There are more than 420,000 ice pieces. The maximum number of collision points is greater than 1.25 million. The porosity is 0.28. The friction coefficient between the ice pieces is 1.35 based on earlier work by Konno et al. (2008). The friction coefficient between the ice pieces and the ship is 0.1 based on the FSICR guideline (Swedish Transport Agency, 2018). The ship speed is 0.482 m/s (5 knots at real scale).

Table 2. Model ship dimensions

	JBC (original)	Resized to Panamax	Model
Scale ratio		1	28.5
Length between perpendiculars	280 m	199.110 m	7.0 m
Maximum beam of waterline	45 m	32 m	1.125 m
Draft	16.5 m	11.733 m	0.4215 m
Ship speed by FSICR		5 kt	0.482 m/s

(a) side view

(b) top view

Figure 1. Geometry model of JBC hull.

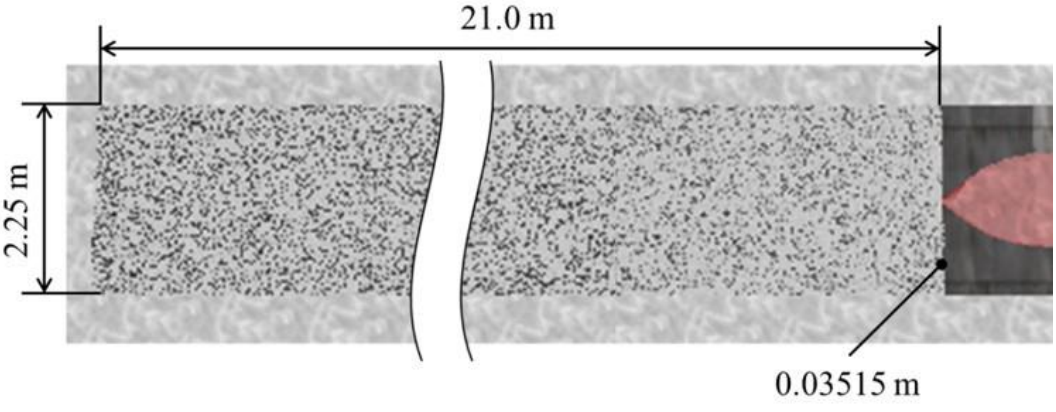


Figure 2. Initial arrangement of ice pieces: top view (21.0 m length, 2.25 m width, 0.03515 m thickness).

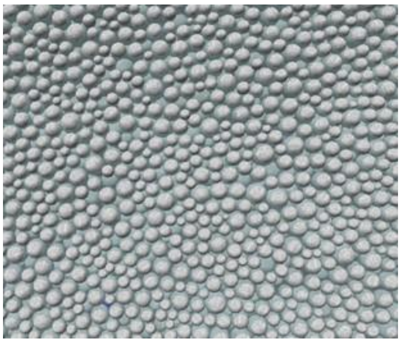


Figure 3. Enlarged view of ice pieces (0.28 porosity).

PRELIMINARY RESULTS

Figure 4 depicts views of the ice pieces from above and below. The analysis showed that the ice pieces exhibited no unphysical behavior such as jumping or entering the ship hull because of the added mass, but moved along the ship hull.

Figure 5 depicts the time variation of the ship resistance in the x, y, and z direction components. From Figure 5, it is apparent that the x-direction has the largest value in the present analysis case, which has the most influence on the resistance. At the start of the analysis, the ship is moving in a channel free of ice pieces, so no effect of ice pieces is found. About 0.4 s later, the ship collides with ice pieces. The resistance starts to increase. While the bow slope section is advancing, the resistance is also increasing. When it advances to the hull parallel section, the resistance variation decreases. The resistance to the ship is greatest when the ship hull is inside the brash ice channel, so it rises and reaches its maximum value at around 15 s. The average value of resistance for 15–40 s is the resistance value on the model scale. The resistance value at this time is converted to the resistance value of the actual ship scale using the cubic law of equation (3). The scale λ in this case is 28.5, as discussed in the preceding section. We compared it with that calculated from the resistance formula of FSICR.

Figure 6 presents the resistance value converted to the real scale and the resistance value calculated using the FSICR resistance formula. The resistance value obtained from the analysis was about 393 kN, whereas the value obtained using the FSICR resistance formula was 999 kN, resulting in the FSICR resistance formula being about 2.54 times larger. The resistance value obtained using the equation of the fluid force proportional to the square of the velocity is 378 kN. The resistance is about 4.15% greater than that with the added mass considered.

$$R_{real} = R_{model} \times \lambda^3 \tag{3}$$

DISCUSSION

For this study, an added mass model was incorporated into the existing fluid force model to evaluate the fluid force on the ice pieces accurately. The conditions of the channel used for the simulation were set assuming Ice Class 1A. The analysis results show no non-physical behavior such as ice pieces jumping or entering the ship hull. They do not sink to the ship's bottom. Ice pieces move along the ship hull. Kim et al. (2019) showed that ice pieces are concentrated around the bow draft line. Our analysis results indicate similar behavior. Therefore, we believe our simulator simulates the motion of ice pieces adequately.

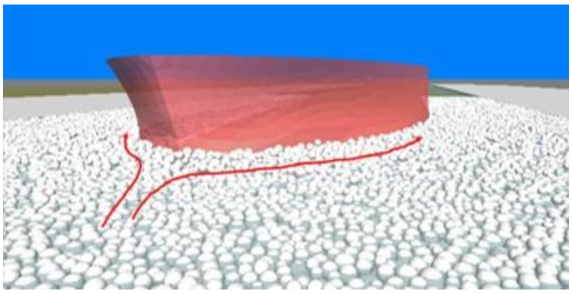
The resistance value calculated using the FSICR resistance formula was 2.54 times larger than that obtained from the analysis. Hellmann et al. (2005) showed that the resistance value obtained using the FSICR resistance equation in Ice Class 1A is twice to three times as large as that obtained using their ice tank test. Therefore, the absolute value of resistance in our simulation appears to be reasonable. The result, however, has not been validated using other methods such as a model test.

The result obtained using the new fluid force model (the added mass model) closely approximates that of the drag-based fluid force model we used in earlier studies. This result implies that the case we examined for this study is inappropriate for comparison of the difference of the fluid force model. A better test case should be developed.

To improve the analytical accuracy, the added mass coefficient must be determined experimentally. Improvements in ice piece shape and the friction coefficient also remain as issues for future study.

CONCLUSIONS

This study was conducted to improve the accuracy of ship navigation simulation in broken ice fields. The added mass model was incorporated into an existing fluid force model to evaluate the fluid force on the ice pieces accurately. The modified simulator was then used to analyze ship resistance in a brash ice channel. Subsequently, the resistance was converted into real-scale values using the cubic law. The calculated value, which was about 2.5 times greater than that obtained with the FSICR resistance formula, conforms to tendencies reported from earlier studies such as one by Hellmann et al. (2005) in that the FSICR formula produced twice or three times greater resistance. Providing "more accurate calculation" as stipulated by the FSICR will be necessary to improve settings of ice piece shape, the coefficient of friction between ice pieces, and the added mass coefficient.



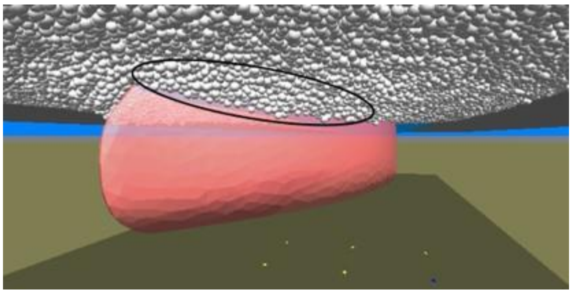


Figure 4. (Left) Motion of ice pieces colliding with the model ship. (Right) motion of ice pieces motion near the bow draft line.

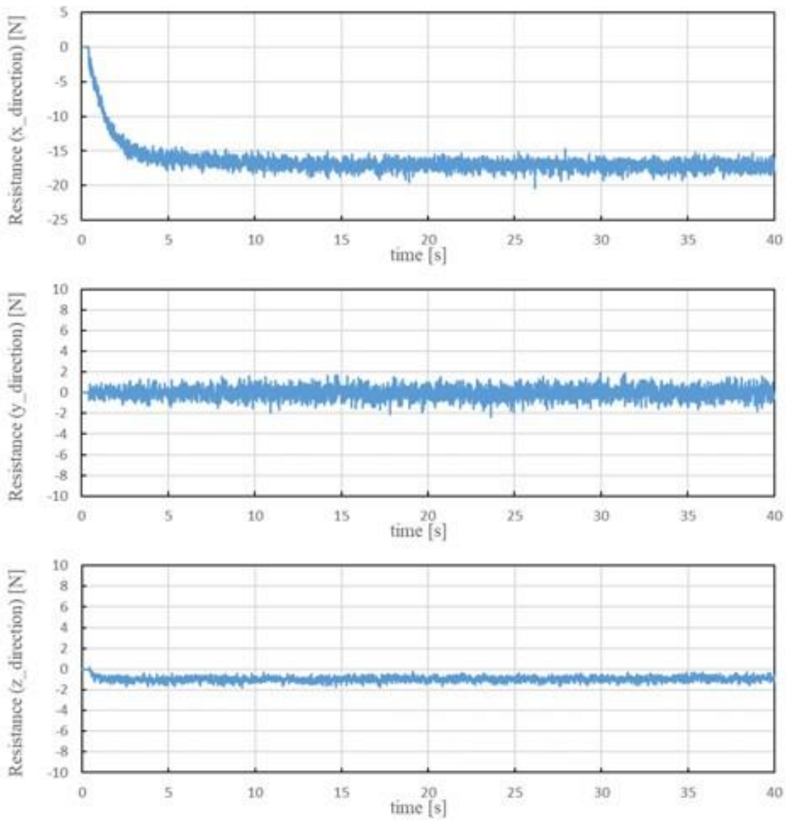


Figure 5. Time history of ship full resistance in x-, y-, and z-directions (0.482 m/s ship speed).

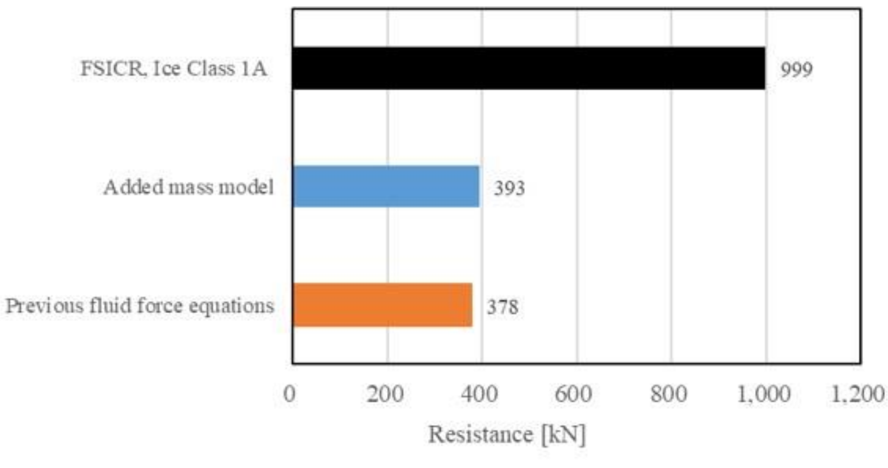


Figure 6. Resistance in real scale.

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