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Numerical investigations of ship–ice interaction and maneuvering performance in level ice

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a solution to the ship–ice interaction problem solved in the time domain by a combined method involving numerical simulations and semi-empirical formula. The breaking process of an intact level ice by an advancing ice breaker has been investigated by a 2D numerical method. An interaction detection technique has been introduced. In order to compute the ice load, a pressure-area relationship for the ice was applied, and a flexural ice plate model was developed. A 3-degree-of-freedom (3DOF) model was adopted to simulate ship maneuvering in level ice. The proposed numerical method has been validated by using the experimental results of an 1:20 scaled CCG R-Class icebreaker model and the full-scale turning circle results.

1. Introduction

The growing interests in oil and gas exploration in Arctic and sub-Arctic regions and in the transportation through the Northern Sea Route have led to extensive research on better understanding of ship–ice interaction and vessels' maneuvering performance in ice covered water. For a ship advancing and turning in level ice, the assessment of ship maneuvering performance needs to be addressed. For a ship advancing in ice, the primary interest is on the prediction of the ice resistance. For maneuvering studies, the transverse force and turning moment are as important as the resistance when the ship is in turning.

It is challenging to predict the resistance that a ship is encountered in the intact ice field. One of the common assumptions, the principle of superposition to the total resistance is widely accepted by many researchers when the global ice load models were developed (for example, Enkvist, 1972; Kashteljan et al., 1969; Keinonen, 1996; Lewis and Edwards, 1970; Lindqvist, 1989; Milano, 1972; Riska et al., 1997; Spencer, 1992). In the past decades, efforts have been made to improve these models and implement them in numerical methods. For instance, Wang (2001) adopted the conceptual framework of the nested hierarchy of discrete events, proposed by Daley (1991, 1992) and Daley et al. (1998), and simplified the method by considering three continuum processes of crushing, bending, and rubble formation. A geometric grid method, which requires the discretization of the entire computational domain, was proposed to simulate continuous contacts between the structure and the level ice. The mechanics of ice crushing-bending failure was applied and the ice loads were numerically computed. This approach has been adopted and modified by many other researchers, such as Nguyen et al. (2009), Sawamura et al. (2009), Su et al. (2010) and Zhou and Peng (2014). Tan et al. (2013) proposed a 6 degree-of-freedom (DOF) ship–ice interaction model by discretizing a belt area around the ship waterline. Their work provided a possibility to include ship heave, roll and pitch motions during the icebreaking process. A further study on the effect of dynamic bending of level ice during ship–ice interaction was carried out with this 6 DOF model by Tan et al. (2014).

Although the fundamental mechanism of icebreaking is not fully understood, many semi-empirical methods were proposed to estimate the resistance of a vessel in ice. However, limited effort has been made on the estimation of the yaw moment for a ship maneuvering in level ice. Lau et al. (2004) proposed a method to estimate the total yaw moment that is analogous to that of ice resistance in the work of Spencer (1992). The total yaw moment was divided into hydrodynamic, breaking, submergence, and ice clearing components. The formulas for the terms associated with breaking and submergence were presented. In their work, the ice-induced forces were considered as three concentrated loads among which two were acting at the bow and the other was on the midship section. The yaw moment was obtained by multiplying those forces and the corresponding lever arm lengths. Martio (2007) developed a numerical program to simulate the vessel's maneuvering performance in uniform level ice based on Lindqvist's ice resistance model (Lindqvist, 1989). The major contribution was to extend the

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analytical formulas to 3 DOF. The effects of bending and submergence forces on sway and yaw motions were taken into account. A relationship between the resistance and the yaw moment, as well as the transverse force, was developed. Only crushing was calculated numerically, and the other two terms were obtained by using analytical formulas. Nguyen et al. (2009) and Su et al. (2010) developed 3DOF ship–ice interaction models. In their work, it was assumed that only the term associated with breaking had effect on sway and yaw motions. The remaining components of ice loads were considered as resistance that only affected the surge motion.

When a ship is maneuvred in level ice, the ship–ice interaction can be described as a continuous process. As the ship moves into the ice sheet, local shear fracture, crushing failure, and vertical deflection occur at the edge. These ice failure modes manifest themselves as a breaking force on the hull. When the stress somewhere inside the ice sheet exceeds its limit, a bending failure will occur which leads to the breaking of ice floes. The broken ice pieces are further accelerated and rotated by the ship until they are parallel to the hull. Subsequently, the broken pieces slide along the hull until they lose the contact with the ship. During this process, two force components are assumed: the buoyancy caused by the density difference between the ice and the water, and the clearing force that is attributed to the accelerating and rotating ice floes as well as the frictional force during ice sliding. The total ice resistance therefore consists of these three components discussed above. In this paper, the breaking process was simulated by a 2D numerical method involving the discretization of ice edges and ship's waterline. The contact loads were calculated, compared with the bending capacity of the ice sheet, and were used to determine the possibility of ice breaking. Equations of ship motions were then solved, and the ice edges were updated. The clearing and buoyancy forces were calculated using published empirical formulas. The effects on sway and yaw motions were taken into account in this paper. A flexural ice plate model was also developed to modify ice loads. Experimental results of the PMM tests of an 1:20 scale R-Class icebreaker ship model were used to validate the numerical method.

2. Modeling of ship–ice interaction

2.1. Coordinate systems and mathematical formulations

As shown in Fig. 1, three coordinate systems are employed in the computations. The earth-fixed coordinate system is denoted as O_e–$X_eY_eZ_e$. The position and heading of a ship is described in this coordinate system. The ship-fixed coordinate system, o–xyz, is with ox-axis pointing to the bow, oy-axis pointing starboard and oz-axis positive downward. The origin, o, is located at the interaction point of the longitudinal central plane, the waterplane and the midship section. Equations of ship motions are solved in the ship-fixed coordinate system; The ice-fixed coordinate system, o_i–$x_iy_iz_i$, is on the ice plate and parallel to O_e–$X_eY_eZ_e$. The coordinates of the discretized points on ice edges are defined in o_i–$x_iy_iz_i$.

The equations of motion for maneuvering, including surge, sway and yaw, are given below:

$$\begin{cases} \dot{x} = \cos(\psi)u - \sin(\psi)v \\ \dot{y} = \sin(\psi)u + \cos(\psi)v \\ \dot{\psi} = r \end{cases} \tag{1}$$

$$\begin{cases} m\dot{u} - mvr - mx_G r^2 = X_H + X_P + X_R + X_{ice} \\ m\dot{v} + mx_G\dot{r} + mur = Y_H + Y_R + Y_{ice} \\ I_z\dot{r} + mx_G\dot{v} + mx_G ur = N_H + N_R + N_{ice} \end{cases} \tag{2}$$

where m and I_z are the mass of the ship and the mass moment of inertia, respectively; x_G is the center of gravity defined in the ship-fixed coordinate system; X, Y and N denote the forces and moment with respect to ox, oy and oz-axis, respectively; x and y are the coordinates; ψ is the orientation; u, v and r denote the corresponding velocities in the ship-fixed coordinate system; the overhead dot represents the time derivative; variables with the subscripts, H, P, R and ice, represent forces and moment due to hydrodynamic force, propeller force, rudder force and ice load, respectively.

2.2. Ice-induced forces

The following assumptions were made in order to simplify the hull–ice interaction problem:

- The intact ice sheet is semi-infinite with uniform thickness. It is stationary with respect to O_e–$X_eY_eZ_e$;
- The hull–ice interaction is a continuous process which involves repeating cycles of contacting, crushing and bending and breaking;
- Superposition principle is applied to the total ice induced resistance;
- Vertical displacement of the ship is neglected;
- Contacting surfaces remain flat during crushing;
- The shape of the broken ice floe is considered circular for computing in the bending failure.

The total resistance due to ice can be written as:

$$\begin{cases} X_{ice} = X_{br} + X_{cl} + X_{buoy} \\ Y_{ice} = Y_{br} + Y_{cl} + Y_{buoy} \\ N_{ice} = N_{br} + N_{cl} + N_{buoy} \end{cases} \tag{3}$$

The breaking force, denoted as $\mathbf{F_{br}} = [X_{br}, Y_{br}, N_{br}]^T$, exists when the ice plate is crushed and bent downward until the breaking occurs. The dynamic clearing force, $\mathbf{F_{cl}}$, acts on the hull as the broken ice floes rotates, accelerates, submerges and slides along the ship. The static force due to the buoyancy of ice is denoted as $\mathbf{F_{buoy}}$. The open-water resistance is considered as hydrodynamic force and is not part of ice loads. Each term in the equation above has effect on surge, sway and yaw motions. The breaking term is calculated numerically based on the detected contacts at each time step. The resistances due to clearing and buoyancy (X_{cl} and X_{buoy}) are calculated using published empirical formulas. The

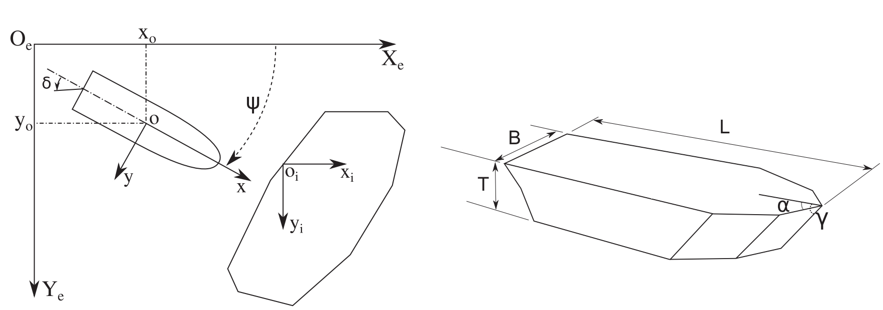

Fig. 1. Three coordinate systems.