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Effect of dynamic bending of level ice on ship's continuous-mode icebreaking

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ABSTRACT

This paper focuses on the influences of the dynamic effects of ship–ice–water interaction on ship performance, ship motions, and ice resistance. The effects of the dynamic bending of ice wedges and ship speeds are especially investigated. The study is carried out using a numerical procedure simulating ship operations in level ice with ship motions in six degrees of freedom (DOFs). A case study is conducted with the Swedish icebreaker Tor Viking II. The 3-D hull geometry of the ship is modeled based on the lines drawing. The predicted performance of the ship is compared with data from full-scale ice trials.

1. Introduction

1.1. Overview of the dynamic process of continuous-mode icebreaking

Continuous-mode icebreaking of ships operating in level ice is a process composed of repeated crushing–bending events of the edge of the channel. The ice edge is subjected to contact loads from the ship hull which moves in six degrees of freedom (DOFs). Model- as well as full-scale investigations (e.g., Ettema et al., 1987, 1991; Izumiyama et al., 1991; Kotras et al., 1983; Lewis and Edwards, 1970; Valanto, 1993) have shown that the failure of ice by bending and the emergence of a new ice edge follow a seemingly regular pattern comprised of sequential breaking-off of wedge- and cusp-shaped ice pieces from the intact ice sheet. The geometry of the ice edge created by the repeated icebreaking is often referred to as the "icebreaking pattern" (e.g., Fig. 1).

Although the repeating cycles of icebreaking are essential elements to the continuous icebreaking process, individual icebreaking events do not act in unison. The ship hull may interact with a whole pattern of icebreaking rather than the individual events. Moreover, hull motions shape the process by significantly altering the loading conditions, namely, the loading rates and loading directions.

Due to these characteristics, the ice resistance experienced by a ship, i.e., the mean value of the longitudinal force induced by breaking and clearing the ice, is determined primarily by the way how the ship interacts with the pattern of icebreaking, i.e., by the characteristics of the ship-icebreaking pattern system.

To be more specific, ice resistance is influenced by the material properties of ice, hull geometry, ship motions, and ship speeds. In nature, these factors are intertwined with each other, which brings more complexity to the dynamic system.

The first ice resistance formulations (e.g., Enkvist, 1972; Kashteljan et al., 1968; Lewis and Edwards, 1970) used to relate resistance directly to a few "primary parameters" characterizing ice properties (thickness, strength and friction), hull size (beam, displacement, etc.), hull form (stem angle, waterline angle, etc.), and ship speed via single formula. These models have been practical engineering tools for early (performance) design of ice-capable ships and generally achieved passable agreements with full-scale measurements.

However, the detailed ship–ice–water interaction mechanisms from where ice resistance arises are included only when they aid the determination of ice resistance. Designers were forced to treat the problem from a macroscopic point of view (Lewis and Edwards, 1970). Effects such as the ship motions, icebreaking pattern, ice friction, local ice pressure distribution, and local loading rates were either rarely touched upon or represented by empirical constants implicitly. Moreover, some of the early models could sometimes be too ship-specific to be extrapolated to different types of ships and thus to satisfy the demands for innovative ship (structure) types and optimizing designs. Later researches have been dedicated to a better understanding of the mechanism and physical nature of the dynamic process of icebreaking (e.g., Daley, 1991; Riska, 1987; Tuhkuri, 1996; Valanto, 1989; Varsta, 1983).

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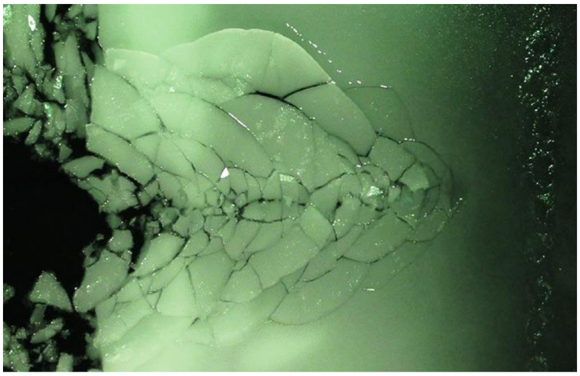
a) Observed icebreaking pattern in Aalto ice tank in Feb., 2012
(Photograph by X. Tan)



b) Simulated icebreaking pattern

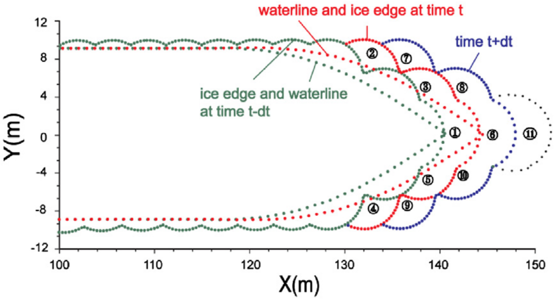


Fig. 1. Example of the icebreaking pattern. (a) Observed icebreaking pattern in Aalto ice tank in Feb., 2012. (Photograph by X. Tan). (b) Simulated icebreaking pattern.

Developments in computational mechanics and graphics have stimulated numerical implementations of mathematical models and made it possible to study the ship–ice–water interaction using bottom-up approaches which enable consideration of detailed ice action mechanisms. Since ice loads are in general both (quasi) periodic and variable, a mean value from analyzing only one icebreaking cycle is not always reliable. Solutions are further sought in the time domain to simulate the whole icebreaking process (e.g., Aksnes, 2010; Liu, 2009; Lubbad and Løset, 2011; Su, 2011; Wang, 2001).

1.2. Present work

Former time domain simulations simulate the repeating icebreaking process using static bending failure criteria of the ice wedge, where the influence of loading rates on the bending failure load was not taken into consideration.

The dynamic effects of ship–ice–water interaction may be of great significance to the icebreaking process in that the ice bending failure load as well as the size of ice pieces is influenced by local loading rates. Moreover, ship's forward speed together with the size of the ice pieces determines the frequency of load peaks and thus influences the dynamic response of the ship.

This paper focuses mainly on the effect of ship speed dependent phenomena in icebreaking on ice resistance and ship performance in ice. In particular, the effect of the dynamic bending of ice wedge due to ship impact is investigated. The investigation is carried out by implementing a dynamic bending failure criterion into a previously developed numerical procedure which simulates the continuous-mode icebreaking in the time domain. This forms the novelty of the paper because a time domain simulator with a dynamic bending failure criterion has not been addressed before. Speed dependence of the icebreaking resistance is investigated using the numerical procedure with a dynamic failure criterion for the bending of the ice edge adopted (referred to as the "dynamic bending model" hereinafter).

The numerical procedure, proposed by Tan et al. (2012) and further developed by Tan et al. (2013), simulates continuous-mode icebreaking with ship motions in six degrees of freedom (DOFs). A static bending failure criterion was then used. However, the application of static solutions to icebreaking speeds has been questioned. The inertial force of the ice and the hydrodynamics of the water foundation, which are sensitive to loading rates, are important factors in determining ice bending failure loads and thus ship performance.

In this paper, these factors related to the dynamic ice bending are taken into consideration. First, a dynamic bending failure criterion for the ice is developed based on the semi-empirical studies provided by Varsta (1983). This is then incorporated into the previously developed numerical procedure. The results from using the dynamic bending model are compared with those from the static model, in a wide range of ice thicknesses and ship speeds. The effects of dynamic bending of ice edge on ice resistance and ship motions are investigated by comparing the results from these two groups of simulations.

The main assumptions and simplifications made in the numerical procedure are as follows:

1) The force superposition principle is applied.

It is assumed that ice floes are cleared by the advancing hull immediately after the bending failure from the intact ice sheet. The resistance from ice floe clearing and submersion is considered not to interfere with the next contact. Similarly, open water resistance is also separated from ice resistance. Thus, the expression for the total resistance of a ship experiences in icebreaking can be written in vector form as:

$$\mathbf{R}_{\mathrm{T}} = \underbrace{\mathbf{R}_{\mathrm{brk}} + \mathbf{R}_{\mathrm{sbmg}}}_{\mathbf{R}_{\mathrm{I}}} + \mathbf{R}_{\mathrm{ow}} \tag{1}$$

where, $\mathbf{R}_{\mathrm{T}}$ denotes the total resistance in ice; $\mathbf{R}_{\mathrm{I}}$ denotes ice resistance; $\mathbf{R}_{\mathrm{sbmg}}$ is the resistance caused by clearance and submersion of broken ice floes; $\mathbf{R}_{\mathrm{brk}}$ is the icebreaking resistance arising from the crushing–bending actions; $\mathbf{R}_{\mathrm{ow}}$ is open water resistance.

The icebreaking force, $\mathbf{R}_{\mathrm{brk}}$, which is the immediate cause for the formation of icebreaking patterns, is calculated numerically by integrating contact forces (obtained via a contact algorithm) along the icebreaking waterline. The magnitude of $\mathbf{R}_{\mathrm{sbmg}}$ is calculated by the empirical formula given by Lindqvist (1989). Propulsion force is estimated by the net thrust in ice, T_{net}, which is determined by bollard pull and ship speeds for a given propulsion power.

2) Ship's open water maneuvering coefficients are constant, i.e., frequency independent.

The total excitation force given by Eq. (1) is then applied to solving the ship's dynamic equations of motion (EOM):

$$(\mathbf{M} + \mathbf{A})\ddot{\mathbf{r}} + \mathbf{B}\dot{\mathbf{r}} + \mathbf{C}\mathbf{r} = \mathbf{F} \tag{2}$$

where, **M**, **A**, **B** and **C** are the mass, added mass, linear damping and hydrostatic restoring force matrices, respectively; F denotes the general force vector determined by resistances (as defined in Eq. (1)) and propulsion force.

Eq. (2) is formulated with respect to a ship-fixed coordinate system so that the coefficient matrices are constant. In this paper, the maneuvering coefficients, **M**, **A** and **C**, are calculated by 3-D boundary element method. Linear hydrodynamic damping is not included because in ice covered water, icebreaking is considered to be the major source of energy consumption.

3) Ice is considered as an elastic brittle material due to the high strain rates associated with icebreaking especially at the forebody (Enkvist et al., 1979). Therefore, lateral deflections for the loaded ice wedges are not considered in the contact algorithm. Local failure