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A six-degrees-of-freedom numerical model for level ice–ship interaction

Xiang Tan [a,*], Biao Su [a,b], Kaj Riska [a,c], Torgeir Moan [a,b]

[a] Centre for Ships and Ocean Structures, Norwegian University of Science and Technology, N-7491, Trondheim, Norway
[b] Department of Marine Technology, Norwegian University of Science and Technology, N-7491, Trondheim, Norway
[c] TOTAL S.A. - DGEP/DEV/TEC/GEO - 06D55, Tour Coupole, 2, Place Jean Millier, La Défense 6 - Cedex 45, 92078 Paris La Défense, France

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ABSTRACT

A new numerical model simulating ship–ice interaction is proposed in this paper. Since icebreaking is in its nature a three-dimensional nonlinear dynamic problem, the numerical model is developed to look into the intricate interaction process by considering ship motions in 6 degrees of freedom (DOFs). The effect on the icebreaking pattern and ship's performance of ship motions in heave, roll and pitch is investigated. Moreover, pressure–area relation is included in calculating the contact force. Semi-empirical method is used in developing the numerical model and the results are validated by comparing with full-scale data from an icebreaker.

1. Introduction

1.1. Review

Ship–ice interaction is a continuous process during which ship motions and the breaking of ice affect each other. Due to the lack of field observations and the insufficient understanding of the physics of icebreaking especially by moving structures, studies are usually done by combining rational theoretical analysis with information obtained empirically, i.e., semi-empirical methods. Global and local ice load models proposed in previous works (e.g. Daley, 1991; Enkvist, 1972; Kashteljan et al., 1968; Lewis and Edwards, 1970; Lindqvist, 1989; Milano, 1973; Varsta, 1983) describing various aspects of icebreaking process have been implemented by many researchers into numerical procedures. One of the basic assumptions that has commonly been accepted is that the total ice resistance can be taken as the superposition of several force components, i.e., icebreaking force, ice floe turning and submergence force and friction force associated with ice contact, although it could be questionable because the force components could be "complicatedly entangled in each other" (Enkvist et al., 1979). Moreover, since open water resistance is usually very small comparing to ice resistance at icebreaking speeds, the coupling between them could be neglected without causing significant error. Thus, the open water resistance and the pure ice resistance are separable (Riska et al., 1997).

One of the earliest attempts including rational analysis to evaluation of ice resistance is the work by Milano (1973), where ice was assumed to bend in a predictable manner, which was defined by the depth ($C_1 l$) and length ($C_2 l$) of cusps (Fig. 1) evaluated based on plate bending theory and full scale observations. Lewis et al. (1983) conducted a study based on a semi-empirical ice resistance model developed by Naegle (1980) which was in turn a further development of an earlier work carried out by Lewis and Edwards (1970). A large database of model– and full–scale tests was compiled to form the empirical coefficients for the analytical model. Enkvist's (Enkvist, 1972) method for evaluating ice resistance components was used significantly. Varsta (1983) developed a mathematical model analyzing the ice load during level ice–ship interaction process. Several aspects of the icebreaking process, such as average ice pressure formulation, effect of shell stiffness, dynamic bending of ice edge, etc., were especially investigated.

The early mathematical models mentioned above provide approaches to rational analysis of various aspects of the ice load. In general, the results showed good agreements with physical tests, and some of them are still being followed today. However, most of the early models are either based on static analysis of forces (as in Milano's and Lewis's model) or capable of simulating only a short period of time (one icebreaking cycle) or with a too simplified hull and ice edge geometry and contact algorithm.

In recent years, efforts have been put to the modification and refinement of the early models. For example, Valanto (2001a,b) presented a 3D finite element model with the hydrodynamic effects of the water underneath on the bending failure of ice taken into consideration. It was also suggested that the large motion of rotating floes after being bent from the ice cover could be modeled by a mixed Eulerian–Lagrangian formulation, which could further promote the direct calculation of ice floe turning and submergence forces. However, the focus was not yet

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* Corresponding author. Tel.: +47 94224670.
E-mail address: tan.xiang@ntnu.no (X. Tan).

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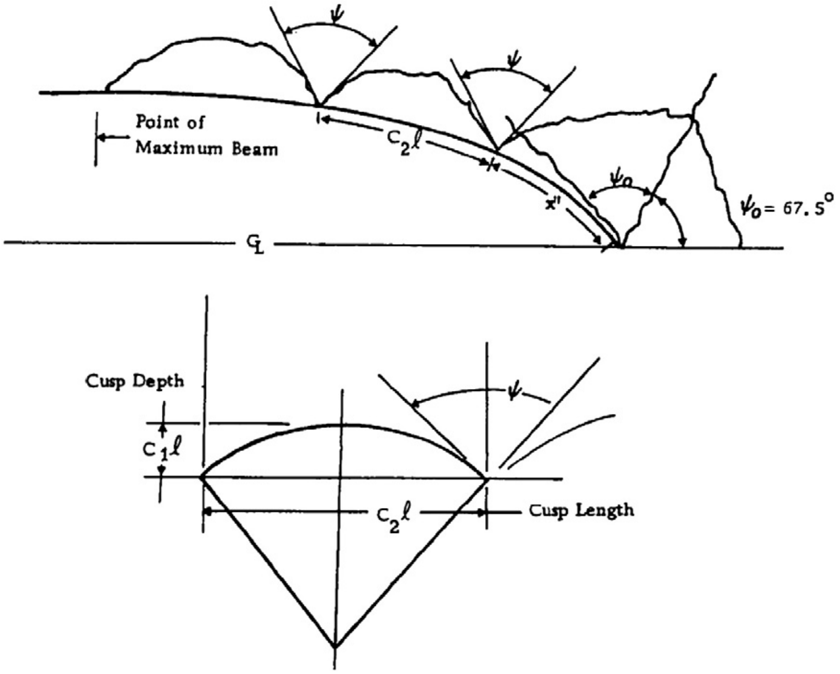

Fig. 1. Idealized bending model of icebreaking (l denotes the characteristic length of ice) (Milano, 1973).

on the study of continuous icebreaking process but on what's going on during one break–displace cycle.

Although the icebreaking cycles are essential elements of the continuous icebreaking process, individual icebreaking events do not act at the same tune. The hull may interact with a pattern of icebreaking, i.e., the process by which a hull's bow opens a sufficiently wide and cleared channel to enable the hull to transit the ice sheet, rather than individual breaking events. Hull motions may affect the cyclic processes by significantly altering contact geometry and loading pattern, resulting in different rates of ice sheet loading. Important noncyclical processes also occur due to non-simultaneous failure of ice around ship's hull (Ettema et al., 1987). These characteristics of icebreaking make it realistic to investigate the problem from a time domain point of view and examine the dynamic process by patterns of icebreaking instead of individual breaking events. Wang (2001) presented a numerical procedure aiming at a time domain solution. The model was based on geometric grid method simulating the continuous contact between a (flexible) fixed conical structure and a moving ice sheet. The work was a continuation of Daley's (Daley, 1991) framework of conceptual ice edge contact model where the ice failure process is, based on observed ice failure events at full scale and model scale, simplified as a nested hierarchy of discrete events including the three continuum processes of crushing, bending and rubble formation. In Wang's work, the focus was on crushing and bending failure, and the process of icebreaking is idealized as successive contact–crushing–bending cycles with predefined bending manner similar to that of Milano (1973). The strategy proposed by Wang (2001) is then followed up by many researchers dealing with different aspects of ships in ice such as dynamic positioning (Nguyen et al., 2009, 2011) and ice resistance and maneuvering (Martio, 2007; Sawamura et al., 2009; Su et al., 2010; Tan et al., 2012, etc.).

1.2. Present work

Since icebreaking is in its nature a three-dimensional nonlinear dynamic problem, it is of interest to look into the intricate interaction process by considering a general picture – that is, a ship moves with 6 degrees of freedom (DOF) – to include the effect of ship motions in heave, roll and pitch on the icebreaking pattern and ship's ice performance.

In this paper, a similar strategy to the one adopted by Wang (2001), which treats the process as successive contact–crushing–breaking cycles, is used; the numerical model is developed by extending the planar model of Su et al. (2010) to a 6-DOF model. First, the continuous icebreaking process is discretized into successive time steps. During each time step, the six coupled dynamic equations of motion for the ship are established, where the icebreaking forces and other external environmental forces are calculated according to the current state variables (orientation, location, velocity and acceleration) of the ship, the current ice edge shape and the ship–ice contact geometry. Then, the equations of motion are solved simultaneously, and incremental displacements are found correspondingly. Since the environmental forces, especially the ice forces, are coupled with the ship's movements, iterations are performed to achieve dynamic equilibrium at each temporal integration point. The state variables of the ship are then updated by the vector sum of the increment and the values at the beginning of the time step. During the icebreaking process, the ship is treated as a rigid body. True geometry of 3D ship hull was modeled using computational geometry methods. Newly formed ice edge due to bending failure is generated according to the indentation of ship's hull into the ice, local contact speed and material properties of ice. The numerical model is implemented into a FORTRAN program. The flow chart of the numerical procedure is illustrated in Fig. 2.

A case study consisting of a series of numerical simulations is then carried out with the icebreaker Tor Viking II. First, simulations with the 6-DOF model are carried out and the results are compared to the full-scale performance data. Then, two reduced-order models are generated by constraining desired degrees of freedom to investigate the effects from ship motions in corresponding directions. Finally, pressure–area relations are implemented to the 6-DOF model to investigate the effect of local contact pressure.

2. Kinematics

2.1. Reference frames

Motions and state variables of the ship and the ice in the model are expressed primarily with respect to two right-handed Cartesian coordinate systems, as illustrated in Fig. 3.