Numerical Simulation Of a Dynamically Controlled Ship in Level Ice

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This paper proposed a numerical method to simulate the ice-induced forces acting on the ship and the performance of a dynamically controlled vessel operating in level ice. The interaction between the ship and the ice was considered by adopting a 2-D Discrete Element Method (DEM). A polygon-based detection technique was applied to determine different contact scenarios. The method was validated with full-scale R-class icebreaker data. Comparisons were made between the simulation, empirical formulas, and sea trial results. Ship maneuvering was simulated by combining the 3 degrees-of-freedom equations of rigid body motions, the Line-of-Sight guidance, and the control system.

INTRODUCTION

The recent increase in hydrocarbon exploration, as well as the requirement of transportation in the Arctic region, has led to a renewed interest in ship maneuvering in ice-covered areas. A vessel operating in an ice field requires a proper dynamic positioning (DP) system to help maintain course keeping or position keeping, which is highly dependent on an accurate numerical model to simulate ice loads. Different ice conditions, e.g., broken ice, level ice, ridge, and iceberg, may be encountered by a vessel operating in the Arctic region. Among these ice conditions, vessel interaction with level ice is of most concern and has been widely studied. There are several methods available in literature for determining level ice-induced resistance, including model tests, empirical and regression formulas, and numerical simulations.

The resistance encountered by a vessel when penetrating into an ice plate primarily depends on the icebreaking process. This process is a repeated pattern that consists of several events (Enkvist et al., 1979). Valanto (1989) conducted an experiment to examine those different events. First, the ice is crushed, accelerated, and turned downward as long as it makes contact with the hull. Crushing and displacement continue as the hull keeps penetrating into the ice plate. When the vertical force reaches the capacity of the plate, bending failure occurs. A piece of ice then breaks down from the plate and keeps turning until it is parallel to the hull. The floe then slides down along the hull until it is cleared aside.

Lindqvist (1989) proposed a set of empirical formulas to calculate ship resistance in level ice. The resistance was divided into crushing, bending, and submerging components, and the influence of speed was taken into consideration. A similar regression model was proposed by Spencer and Jones (2001), which was based on a model-scale/full-scale test of Canadian Coast Guard Ship (CCGS) icebreakers.

In an attempt to numerically simulate the icebreaking process and time history of ice loads, Wang (2001) proposed a Discrete Element Method (DEM) for the force of an advancing ice field towards a fixed conical structure. The method was derived from the empirical formula proposed by Kashtelyan (Kerr, 1975). The size of the broken ice floes was calculated based on the speed and characteristic length of the ice. The method was then extended by Sawamura et al. (2009), Nguyen et al. (2009), and Su et al. (2010) to study ship maneuvering and hull-ice interaction. Liu et al. (2006) proposed a different DEM model to numerically study ship interaction with level ice. In their method, the ship waterline was discretized into points based on the current position and orientation. The breaking and clearing forces were calculated for each waterline point, where applicable, then summed to give a total breaking and clearing force. Two 90° wedges would be broken off the plate when flexural failure happened. They investigated not only the resistance, but also the lateral force and yaw moment. The relations between the turning circle radius, yaw moment, and channel width were also presented. Lau (2011) continued their work by combining the ice-hull interaction model with a motion solver so that ship maneuvering in level ice could be simulated.

Apart from the DEM method, Valanto (2001) proposed a 3-D method, which was based on unsteady potential flow theory, to investigate ice resistance at the ship waterline. The resistance of underwater ice was calculated with the empirical method proposed by Lindqvist (1989). Lubbad and Loset (2011) developed a complete modeling method, which was able to simulate the rigid body motions in 6DOF and all ice floes of varying sizes. In their work, large floes behaved similarly to level ice and flexural failure would occur, while small floes would be pushed aside or rotated and submerged. In addition, Lau (2006) presented the detailed results of the Planar Motion Mechanism (PMM) model test of the Terry Fox icebreaker ship. Moreover, Peng and Spencer (2008) presented the simulation of a dynamically positioned Floating Production Storage and Offloading (FPSO) vessel during offloading operation in open water. A ship motion solver was derived and coupled with a DP model. A Proportional Integral Derivative (PID) control algorithm was applied to maintain position and heading.

The aim of this paper is to propose a method for simulating the behavior of a DP vessel operating in level ice. It is emphasized that the coupling between the vessel motion and icebreaking should be taken into consideration. A similar strategy (Su et al., 2010) is applied to develop a ship-ice interaction model that requires the discretization of both the ship waterline and ice edge. A different contact detecting method is introduced that requires fewer discrete elements. The interaction is investigated in the ship-fixed frame so that the ice edge can be updated at each time step. A guidance

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