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Interaction between Level Ice and Ship Hull based on DEM simulations

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For ship navigating in ice fields, ice load acted on the ship hull is a significant factor for the structural safety and navigation operability. In this study, the discrete element method (DEM) is applied to simulate the interaction between the level ice and ship hull. The level ice is constructed with boned spherical elements under the buoyancy of current. The bonded elements will be broken when the inter-particle strength reaches the bonding strength. The ship hull is constructed with triangular elements without considering its deformation. The breaking process of ice cover and the size distribution of broken ice floes can be obtained from the DEM simulations. The influences of the ice thickness and navigation speed on the dynamic of ice load are analyzed considering the breakage mechanism of ice cover. Ice loads in each contact pair are determined through the contact detection between ice particle element and ship hull element. The global resistance on the ship is determined by summing the contact forces between ice elements and hull elements. The simulated results from the DEM are compared qualitatively well with the existing field data and other numerical results. This work can be aided in the hull structure design and the navigation operating in ice-covered fields.

1. Introduction

In view of the scientific investigations, oil and gas exploitations as well as marine transportation in polar region, more attention has been paid to shipping performance in ice covered waters. Studies on ship navigating in ice have been conducted by field measurements and laboratory experiments. Riska et al. (2001) observed the ice performance of the Swedish Multi-Purpose icebreaker for Viking II (Riska et al., 2001). Kotisalo et al. (1999) measured the ice load onboard MT Uikku during the ARCDEV Voyage (Kotisalo et al., 1999;).

Discrete element-based models have some advantages over continuum-based models, mainly because the fracture propagation is discrete in nature. In some FEM schemes, the initial point of the fracture must be artificially introduced, and subsequently the propagation is simulated. In contrast, the initiation crack point in DEM simulations is defined by the broken bonds between the discrete particles, without any external intervention (Torres,2013). Arttu and Jukka(2013) partly consolidated ice rubble using a two-dimensional combined finite-discrete element method (Arttu et al.,2013). A six degrees of freedom numerical model for level ice-ship interaction in level ice is developed in 2013 (Tan et al.,2013). Ji et al. (2013) adopted the 3D disk element to simulate the ice floes and calculated the global resistance on ship hull (Ji et al., 2013a). In the DEM simulation of interaction between ice cover and offshore structure, the bonded model and relative parameters have been validated with the flexural and compressive strength tests (Ji et al., 2012). The boned models have been proposed in the fracture studies of continuous material such as the concrete and ice, for example, a discrete-element model was developed to study the behavior of viscoelastic materials that are allowed to fracture in glacial ice model (Riikilä et al., 2015).

In this paper, the discrete element method is developed to simulate the interaction between level ice and an ice breaker. The global resistance on hull is calculated with the collision between the ice element and the hull structure. The influences of ice thickness and ship speed on global resistance are discussed.

2 Discrete Element Method for Level Ice and Ship Hull

2.1 Discrete element method for level ice

In the DEM simulation of interaction between level ice and ship hull, the ice cover is constructed with 3D bonded spherical elements considering the buoyancy, gravity factors. For the boundary conditions of the computational domain, a set of springs are placed on the boundary elements in vertical direction. The boundary elements are fixed by a rigid wall in horizontal direction considering the resistance of far field ice cover under natural conditions, as shown in Figure 1. Here, a small area of ice cover is zoomed out to show the packing pattern of ice elements.

The parallel-bond glue placing between the particles can transmit both force and moment which in normal direction and shear direction associated with the parallel bonded models, denoted by F_n, F_s, M_n and M_s, as shown in Figure 2.

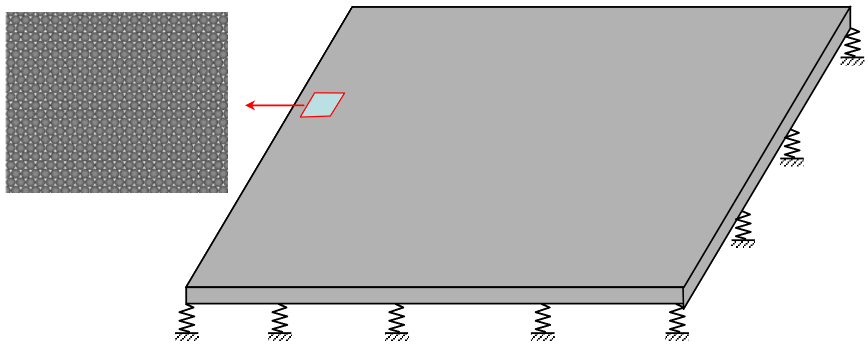

Figure 1. Construction of level ice cover with bonded spheres.

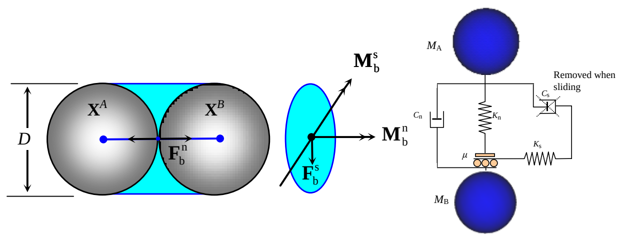

Figure 2. Parallel bonding model and contact force model of sea ice elements. a. Parallel bonding model and b. Contact force model

The maximun tensile and shear stresses acting on the bonding region are calculated based on the beam theory as (Ji et al.,2012):

$$\sigma_{\max} = \frac{F_n}{A} + \frac{M_s R}{I} \quad \textbf{[1]}$$

$$\tau_{\max} = \frac{F_s}{A} + \frac{M_n R}{J} \quad \textbf{[2]}$$

Where A, R, I and J are the area of the transversal surface, radius, polar moment of inertia and moment of inertia respectively.

The hydrodynamic force in the DEM simulation is simplified as a drag force component：

$$F_d = -\frac{1}{2} C_d \rho_w A (V_i - V_w) \quad \textbf{[3]}$$

Where C_d , ρ_w and $V_i - V_w$ are the drag force coefficient(0.15 in the simulation), water density and the relative velocity between water and ice respectively.

2.2 Construction of ship hull

The ship hull is constructed with triangle elements without considering the deformation of hull structure. Here, considering the scale of icebreaker *Snow Dragon* with length 160m, height 14m, width 27m and draught 9m, ship hull is divided into 1430 triangular elements and 763 nodes, as shown in Figure 3a. And the structure hull is simplified as a rigid surface. The contact modes between ice spheres and hull triangular mainly include three different patterns, i.e., sphere-corner contact, sphere-edge contact and sphere-plane contact, as shown in Figure 3b.

Figure 3. Constructions of the ship hull. a. Triangle elements and b. contact model.

3. Ice Load Calculation on Ship Hull with DEM Simulation

In the DEM simulation of interaction between level ice and ship hull, ship velocity is constant. Here we ignore the ice-induced vibration and deformation of hull structures, and the boundary elements are fixed static under the function of the boundary condition. The main computational parameters are listed in Table 1. The inter-element bonding strength of level ice is a key parameter to affect the ice loads. Moreover, the compressive and flexural strengths of sea ice have been simulated with DEM in the investigations of interaction between sea ice and offshore structures (Ji et al., 2012, 2013a, 2013b). In this study, the contact time will be determined according to the linear contact model:

$$T_{bc} = \frac{\pi}{\sqrt{\frac{2K_n}{M}(1-\zeta_n^2)}} \quad [4]$$

Where K_n, M and ζ_n are the stiffness coefficient, mass and damping coefficient**.**

In order to capture the sufficiently detailed collision process, the time step is set as:

$$\Delta t = \frac{1}{30} T_{bc} \quad [5]$$

Table 1. Computational parameters in the DEM simulation

Definition	Symbol	Values
Sea ice density	ρ	970 kg/m^3

Ice cover size	$L \times B$	200m ×80m
Ice thickness	H_i	0.6m
Maximum bonding strength	σ_{max}	1.2 MPa
Normal stiffness of ice particle	K_n	3.8 $\times 10^7$ N/m
Ice element friction coefficient	μ_{pp}	0.3
Ice element restitution coefficient	e_{pp}	0.4
Hull-ice friction	μ_{wp}	0.1
Hull-ice restitution	e_{wp}	0.3
Ship speed	V_{ship}	1.028m/s
Ice element number	N_p	51072
Time step	Δt	47.029 $\times 10^{-6}$s

Figure 4 shows the simulated ice-hull interaction process from different perspectives respectively, captured from the IceDEM1.0 software. We can find the ice cover is crushed at the front of the bow area and piled up at the shoulder area. Here, the inter-element contact force is displayed in different colors. We can find the high pressure zone appears in front of the bow, and the level ice is broken into blocks around the ship hull. When the ship has pulled into the ice zone, a water channel is generated under the function of ice clearing. The ability of ice-clearing is a fatal part of the global resistance, so in the near future, the ability of ice-clearing and the fracture size will be investigated to reveal the organism of ice breaking.

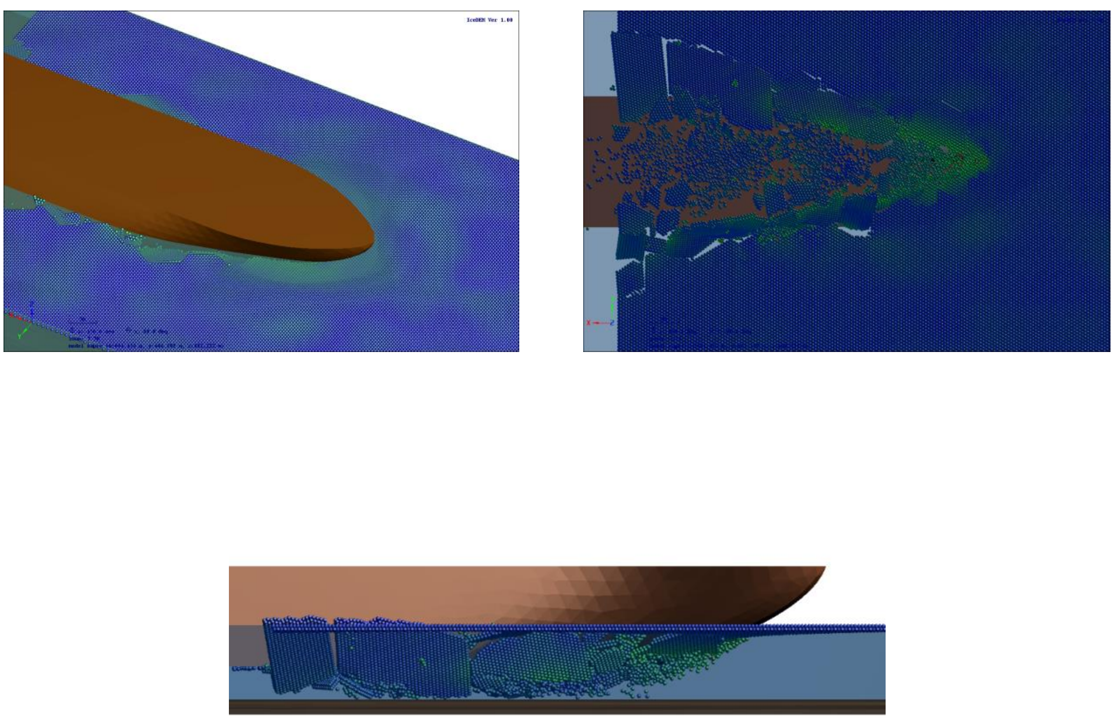

Figure 4. Snapshots of a sailing vessel in the level ice zone. a. Top view, b. bottom view and c. lateral view.

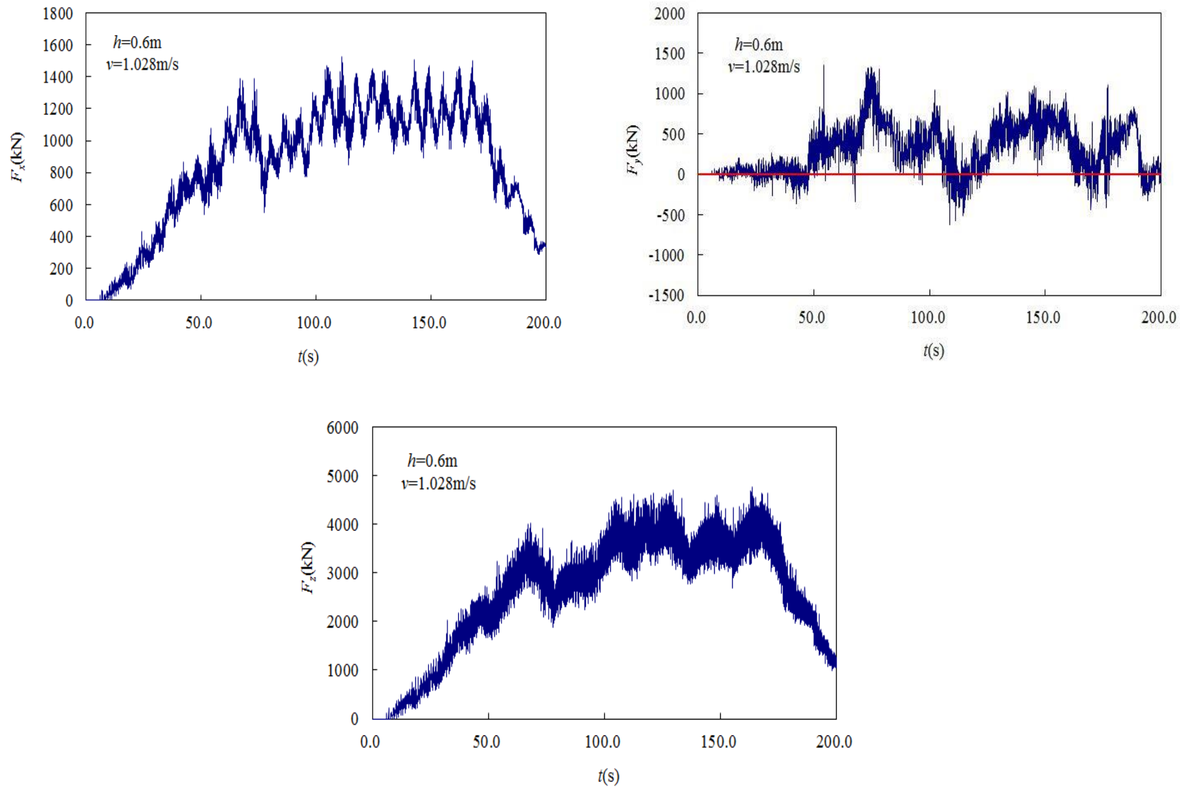

Figure 5. Dynamic ice loads on the ship hull in *x*, *y* and *z* directions. a. X direction, b. y direction and c. z direction.

The global resistance acted on the ship hull is determined by summing the contact forces between ice element and hull element. From the Figure 5, during the process of navigating, the ice loads in *x* and *z* directions increase from zero, then reach steady state with a certain fluctuation accompanying the breakage of ice cover. When the running length approaches 70m (the longitudinal length of the bow), the global resistance is in a steady state relatively. When the ship runs out the ice field (after 160m), ice loads on the bow disappear and frictions on the broadsides decrease rapidly. During the steady phase, the maximum and mean of the ice loads are 1527kN and 1153kN in *x* direction, 4706kN and 3562kN in *z* direction. As the ice-ship model is symmetric, so ice load is relative symmetric in the bow area and the ship navigates in an almost straight line with minor yaw angle. From the Figure 5b, ice load(y direction) fluctuates around zero during the ship running through of ice cover.

The global resistance on ship hull mainly includes two portions: one is bending and crushing from the bow, and the other is from the friction of broadsides. When the ship navigates from open water into level ice zone, the ice force on bow generates and increases with the inter-particle crushing into the water. Meanwhile, the broadsides frictions increase obviously with the fracture length. As the ice particle impact at the ship hull at each time step, ice load will be generated at the contact area.

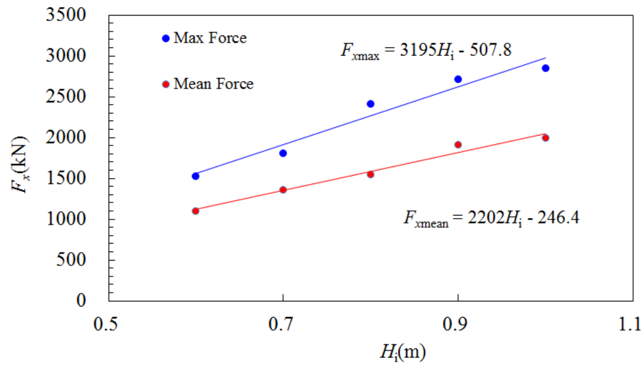

Figure 6. Maximum and mean ice load on ship hull in steady phase simulated with different ice thicknesses (Navigating velocity:1.028m/s).

Here, we set ship velocities from 1.0m/s to 3.0m/s to analyze the influence of velocity. The maximum and mean ice loads in the steady phase are plotted in Figure 7. It shows that the maximum and averaged ice loads increased with the navigating velocity. The averaged ice load is about 450kN with an ice thickness of 0.6m, a velocity of 1.0 m/s. To calibrate the DEM numerical approach through other researchs, Su et al. (2010) calculated the ice loads on the icebreaker AHTS/IB(Su et al. ,2010). Although the simulation was performed by different methods and different ice-breakers, the results can be referred to verify the present DEM results. The maximum and averaged ice loads have the same order of magnitude with the results of this study.

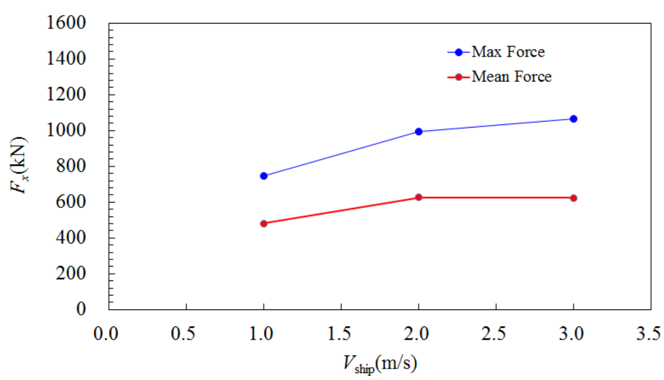

Figure 7. Maximum and mean ice force in steady phases simulated with different ship velocities (Ice thickness:0.6m).

6. Conclusions

In this study, the global resistance acted the on ship hull in level ice is simulated with DEM under different ice thicknesses and ship speeds. To calibrate the DEM numerical approach and the material parameters, it is important to compare the simulated results with field data. In the near future, we would like to compare the present results with the full scale field data of other ships qualitatively and to confirm the feasibility of DEM in ice load simulation on hull.

Moreover, ship maneuvering performances will be the research point in the near point. The local pressure on the bow and broadside areas will also be analyzed to reflect the feature of high pressure on ship and to analyze the strength of hull structure.

Acknowledgments

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