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A numerical method to simulate ice drift reversal for moored ships in level ice

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ABSTRACT

This paper aims to present a new tool to simulate ice-structure interaction in 6 DoFs in time domain. The local force and global force introduced by ice as well as response of the structure are simulated. The goal is to simulate ice drift reversal case which represents the most severe conditions for level ice- hull interaction. An intact ice sheet is divided into squared ice grids and the length of each ice grid is taken as ice breaking length, which may be derived from model tests or field measurements. Both ice breaking process and ice accumulation process are included in the numerical model Based on physical observation, both bending and crushing failures are considered to calculate ice breaking force during ice interaction process. The hull waterline is updated at each time step to estimate precisely the local contact area between ice and hull. After new ice blocks fragment from intact ice, the ice rubble transport underwater and the corresponding ice rubble action on the structure are also calculated according to ISO (19906) code, where some modifications and assumptions are made to fit realistic ice-structure contact situations. The simulations are also well compared to the previous research. The result shows that the numerical tool is promising to simulate the intact ice-structure interaction.

1. Introduction

Moored ships are of great importance to oil exploration and exploitation in ice-infested waters. The study of moored ships in ice-covered waters is of interest to oil exploration and exploitation. Relevant industrial experience with moored structures has been obtained from drilling operations in the Beaufort Sea (Wright, 1999). Turret moored drill ships that operated in the Beaufort Sea include CanMar's drill ship in the 1970s and 1980s and the conical drilling unit, Kulluk in the 1990s. More information about moored structures came from a number of model tests conducted by Comfort et al. (1982), Evers et al. (1983) and Nixon and Ettema (1988). Comfort et al. (1999) assembled an extensive set of ice model test data for floating and moored structures and presented the data in a common format to identify overall trends, and the Kulluk is also included as a typical structure.

Aksnes et al. (2008) and Bonnemaire et al. (2008) carried out ice model tests of an arctic tandem offloading terminal with a focus on mooring forces in level and ridged ice. Later, Aksnes et al. (2010) and Bonnemaire et al. (2010) conducted ice basin tests on a moored offloading icebreaker in variable ice drifting directions.

Although model tests are deemed at present to be the best method of studying the action of ice on moored ships, the model test results could not be used directly for design in the most cases since the ice properties of model ice may differ from the target significantly (Aksnes, 2010). Therefore, numerical tools are expected to assist the model tests for initial studies and actual design of marine structures in ice-infested areas. To assist the model tests and the actual design and operation, numerical simulations of structures in level ice have been done by several researchers. Valanto (2001) calculated ice loads on the design waterline of several vessels and obtained local ice load distributions on hulls when the ships advance straight and turn in level ice. The submersion force is derived on the basis of empirical formula. The maximum forces on the waterline were computed and compared with model scale measurements for a coast guard ship. The correlation between the simulated results and the measured short-term ice loads was satisfactory. The discrete element method (DEM) was first tried to simulate the interaction between moored ship and broken ice by Hansen and Løset (1999). This method was further developed to study ship maneuvering performances at NRC (Lau et al., 2011; Zhan et al., 2010). The predictions were in good agreements with model test results. Karulin and Karulina (2011) extended DEM simulation to investigate the behavior of a moored tanker under a change of ice drift direction. The simulation calculations were validated well by comparing experimental data.

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Sayed and Barker (2011) applied the Particle-In-Cell method based on a hybrid Lagrangian–Eulerian formulation to simulate the interaction between broken pack ice and a moored Kulluk platform. Aksnes (2010) presented a semi-empirical method incorporating probabilistic models based on the model test results. However, this model is limited to one-dimensional simulations in the surge direction only. Zhou et al. (2011, 2013) presented a 2D method in the horizontal plane for simulating level ice-hull interaction process, where the ice load during submersion, sliding and accumulation were simplified based on empirical and analytical methods. It is a basic study of moored ship in ice, and validation was conducted through a standardized scaling up technique of Wright (1999).

As an extension of the previous study, the present paper proposes an improved method to simulate a special scenario of ice-moored ship interaction where the ship may be subject to high ice force and large excursion. It is called ice drift reversal which is taken as the most severe condition for moored ship-shaped structure in ice-covered waters. It occurs when the drifting ice is changing direction suddenly and attacking the hull at an angle of around 180° anti-clockwise. The ship intends to rotate and heads into the drifting ice. In this study, both ice loads and response of moored ship in ice drift reversal case are simulated and analyzed.

2. Equation of motion

Two reference frames are used, namely the global and local frames. The global coordinate is earth-fixed, denoted as $X_EY_EZ_E$, is placed so that the X_EY_E plane coincides with the water surface, and the Z_E axis is positive downwards. The local coordinate is ship-fixed frame with Z vertically upward, X in the direction of forward motion, Y directed to the larboard and the origin at the hull's center of gravity. The configuration of two frames is shown in Fig. 1. The 6 DOF nonlinear dynamic equations of motions in the body fixed frame can be conveniently expressed as:

$$(M + A)\dot{v} + D(v)v + g(\eta) + \mathrm{F}_m(\eta) = F \tag{1}$$

$$\dot{\eta} = J(\eta)v \tag{2}$$

where dot means the time derivative. η denotes the position and orientation vector in earth fixed reference frame. v is linear and angular velocity vectors which are decomposed in the body fixed frame. M is the inertia matrix and added mass A is calculated from a boundary element method routine. $D(v)$is the damping matrix. $g(\eta)$ is the vector of gravitational/buoyancy forces and moments. $\mathrm{F}_m(\eta)$ is restoring force due to mooring systems. F is the environmental loads which may be caused by wind, waves and currents, ice, etc. $J(\eta)$ is the transformation matrix between the body fixed and the earth fixed reference frames.

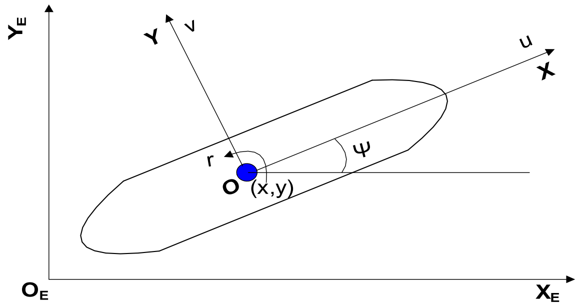

Fig. 1. Global and local reference frames in the horizontal plane.

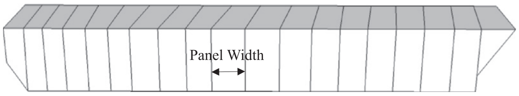

Fig. 2. Schematic of hull panels (not in scale).

Considering low speed of moored ship in ice, the damping, restoring, and buoyancy forces and moments can be linearized about v ≈ 0. Then we get C(v) ≈ 0, D(v) ≈ D (radiation damping). For surface vessels it is convenient to use a linear approximation (Fossen, 2002):

$$\mathrm{g}(\eta) \approx \mathrm{G}\eta = \mathrm{diag}\{0, 0, \rho g A_{wp}(0), \rho g \nabla \overline{GM_T}, \rho g \nabla \overline{GM_L}, 0\}\eta$$

where ρ is the density of water, g is the gravity acceleration, $A_{wp}(0)$ is the area of the waterline, ∇ is the displacement of the hull, $\overline{GM_T}$ is the transverse metacentric height, $\overline{GM_L}$ is the longitudinal metacentric height.

Then it makes sense to approximate Eq. (1) by

$$(M + A)\dot{v} + Dv + G\eta + \mathrm{F}_m(\eta) = F \tag{3}$$

To solve the equations of motion that were established above numerically, Runge-Kutta method was deployed.

3. Numerical model

In the developed numerical model, the hull is divided in vertical panels along longitudinal axis in 3D (shown in Fig. 2) and the ice forces in horizontal and vertical planes on each panel are estimated at each time step. The total ice forces on the structure are calculated as the sum of all local ice forces. The ice force consists of ice breaking force and ice accumulation force. The ice breaking force mainly considers interaction of intact ice and structure at the waterline while the ice accumulation force considers the impact of broken ice floes fragmented from intact ice around the hull underwater.

Ice breaking force is mainly acting on the waterline of the structure. Two kinds of icebreaking failures, namely bending failure and crushing failure, are considered, depending on the local slope angle of the structure, where ice collides with the structure. If the slope angle is small, ice force due to bending failure is included. On the other hand, if the slope is very steep or nearly vertical, ice force due to pure crushing is considered. As for crushing failure, the resulting ice force is calculated according to ISO. Reference is made to Zhou et al. (2017). We will not go to details herein. Ice breaking force caused by bending or crushing failures is assumed to act on waterline of the structure. Once the local ice breaking is calculated, the resulting moments of force around three axes in local reference frame could be derived. Both ice breaking failures are described as follows.

3.1. Ice bending force

The ice load on a moored ship in unbroken ice depends significantly on the interaction process by which the hull breaks and displaces the ice. Once the ice contacts the hull, ice is being crushed. The crushing force then increases with increasing contact area until its vertical force component gets large enough to cause bending failure of the ice. During this process, only crushing takes place on the contact surface. The resultant crushing force F_{cr} could be expressed as

$$F_{cr} = A_c \sigma_c \tag{4}$$

where A_c is the contact area between ice and hull, σ_c is the effective crushing strength, which could be derived from model scale and full scale measurements. According to Timco and Weeks (2010), the crushing strength ranges from 0.5 to 5 Mpa for first year ice and 7 to 15 Mpa for old ice.

In order to calculate the contact area A_c, some parameters have to be defined. As shown in Fig. 3, L_h is calculated from the distance between two crossing points between ice grid and hull, and L_d is calculated from the perpendicular distance from the cusp of ice nodes to the contact surface. According to Fig. 4, the two cases considered herein, the contact area could be expressed as: