Cold Regions Science and Technology 138 (2017) 36–45

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Validation of a numerical model for iceberg towing in broken ice

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ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form 20 February 2017
Accepted 4 March 2017
Available online 07 March 2017

Keywords:
Iceberg
Sea ice
Ice management
Discrete element method
Contact dynamics
Numerical model

ABSTRACT

The possibility of iceberg towing in broken ice is attracting considerable interest because it may help to improve the design of offshore structures to be used in regions where both sea ice and icebergs can appear simultaneously. The contribution of the broken ice resistance to the total towing force still remains uncertain. A model of iceberg towing in broken ice has been proposed and discussed (Yulmetov et al., 2016), and it requires validation. The present paper aims to validate the model and to provide an estimate of the broken ice resistance. The validation is performed using data obtained in a model-scale towing experiment in the Hamburg Ship Model Basin. The evolution of the towing force and mean towing forces calculated in the simulations are compared to the experimental results. A qualitative analysis of the broken ice field after towing is given. The numerical model reproduces the average towing forces measured in the experiment fairly well. In addition, the scaled results of the simulations are compared with the existing analytical approximations of the ice resistance to drifting icebergs. The numerical model can be addressed when planning towing operations in ice; however, further testing against full-scale data would significantly improve its credibility.

1. Introduction

Ice management may be performed in close proximity to an offshore structure to reduce or avoid actions from any kind of ice features (Eik, 2008). Its major components are detection, tracking, forecasting, threat evaluation tools, physical ice management, and emergency disconnection system. Icebreaking and iceberg towing are two possible means of physical ice management that are usually considered separately. The first reduces ice actions on a structure by reducing ice floe size using icebreakers working upstream (Hamilton et al., 2011). The second attempts to reduce the possibility of collision with an iceberg by deflecting it from the structure (McClintock et al., 2007). Towing of icebergs has been successfully performed a number of times in open water, but how feasible is it when sea ice is present?

In conditions where icebergs drift together with sea ice, towing operations become challenging. Sea ice creates additional resistance to an iceberg, and the magnitude of the ice-induced force during towing still remains unknown. It is possible to make a channel in the sea ice and reduce the floe size in order to reduce resistance during towing. However, it is unrealistic to fully exclude the broken ice from the interaction process with the iceberg.

To date, only a few attempts to tow an iceberg in icy conditions have been made. Two cases are reported for the Barents Sea, where icebergs in sea ice are expected at the Shtokman field. In April 2004, a bergy bit of approximately 15.5 thousand tons was towed in less than 10 cm thick ice of 90% ice concentration (Marchenko and Gudoshnikov, 2005). The following year, a 200 thousand tons iceberg was towed in thicker but more fragmented ice (Marchenko and Ulrich, 2008). The iceberg started to rotate when the towing vessel encountered a large ice floe and lost speed. This caused increased tension followed by the breakage in one of the towing line branches when the towing vessel accelerated again. Icebergs in pack ice at the Grand Banks may be expected approximately one out of six years. Randell et al. (2009) mentioned a case of towing within sea ice that took place in 2008; however, no detailed description was provided. Also, icebergs in sea ice are often present at the Kanumas area in the Greenland Sea (Hamilton, 2011) that have been considered as a promising offshore field for hydrocarbons.

In addition to iceberg towing in ice, there are tasks related to the towing of large structures in ice. As an example, in 1983 Kulluk was towed on the drilling site through approximately 0.5 m thick level ice. The transit off site occurred in fragmented, 1–1.5 m thick ice of 20–70% ice concentration (Loh et al., 1984). Also, a semi-submersible accommodation hull was towed in the Bohai Sea in January 2013 (POSH Terasea, 2013). The ice was 10–20 cm thick, consisting of large and unmanaged floes. The towing operation ended successfully after two days.

As stated above, there is a lack of full-scale data for towing of icebergs or large structures in broken sea ice. The experimental research is limited to the experiments carried out at the Hamburg Ship Model

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http://dx.doi.org/10.1016/j.coldregions.2017.03.002
0165-232X/

Basin (HSVA) ice basin (Eik and Marchenko, 2010). The tests were performed for various ice concentrations, iceberg shapes and towing scenarios. It has been found that the ice concentration had the strongest effect on the towing force after velocity, acceleration and towing course changes. Towing forces measured in these few tests can be used to validate the numerical model presented by the authors in the previous paper (Yulmetov et al., 2016).

In addition to the experiment, there exist two numerical estimates of sea ice resistance to the movement of icebergs. First, the sea ice resistance given by Lichey and Hellmer (2001) can be calculated for large icebergs. In their study, the ice resistance force is assumed to be zero for ice concentrations below 15%; for higher concentrations, the ice is treated as a viscous material; and for concentrations above 90%, the iceberg is captured by ice, but the resistance is limited by the sea ice strength given by Hibler (1979). The approach works well when the ice can be treated as a continuum in relation to an iceberg, but its validity is questionable when the ice floe size is comparable to that of the iceberg. The second estimate has been given by Marchenko et al. (2010) and is based on the assumption that the ice resistance force is associated with the work spent on the creation of a channel of unit length in the broken ice.

Our recent model of an iceberg being towed in broken sea ice was proposed and discussed in (Yulmetov et al., 2016). The model is based on the non-smooth discrete element method (DEM) applied to model the broken ice, and its details are presented in Section 2. In this paper, we validate the model using the mentioned experiment described in Section 3. The results of the simulation are presented in Section 4. We then compare the scaled experimental and numerical results with known analytical approximations of the ice resistance, and discuss what a potential full-scale towing of iceberg in ice may entail. With a good match between the simulations and experiment, the model can be proposed for decision support in the design and planning of towing operations of icebergs in broken ice or at least can be used to simulate model-scale towing experiments.

2. Numerical method

2.1. General description

Pack ice consists of discrete floes with a size from a few metres to kilometres. When icebreaking is applied, the upper limit of the floe size can be reduced to a few tens of metres. On scales comparable to the floe size, the ice should be treated as a discontinuous material, which means that every ice floe and iceberg should be modelled as a distinct rigid body. The non-smooth DEM has been found capable of simulating ships and floaters in broken ice (Kjerstad et al., 2015; Lubbad and Løset, 2011) and it has been developed to simulate iceberg towing in ice (Yulmetov et al., 2016).

This planar model detects contacts between floating ice features and estimates forces at the contacts using discretized momentum equations. In contrast to the traditional DEM integrating the equations of motion on time scales much shorter than characteristic collision duration, the non-smooth DEM makes time steps comparable to the collision duration resulting in abrupt velocity changes between the time steps. As a consequence, the accelerations and the forces are not resolved during the collision period. Instead, the non-smooth DEM calculates impulses that are in fact momenta exchanged between bodies in contact. So, the large time step results in much faster calculations, but at the same time it complicates collision force estimations.

The equations of motion are formulated in a frame of reference with a fixed origin. When simulating basin-scale experiments, the origin is located on the water surface, at the middle of the short side of the basin, and the x-, y-axes are directed along and across the basin. For the full-scale simulations, the origin is located at the water surface at the initial iceberg's position, and the axes are directed northward and eastward.

When ice features are in contact, the contact force component that acts along the contact normal pushes them apart. Following Yulmetov et al. (2016), the velocities of N_b ice features participating in N_c contacts may be projected on contacts' normals:

$$\mathbf{w} = \mathbf{JU} + \mathbf{b} \tag{1}$$

where $\mathbf{w}$ is N_c component vector of normal contact velocities, $\mathbf{J}$ is a $3N_b \times N_c$ Jacobian of transformation from Cartesian coordinates into normal separation distances between the bodies participating in contacts, and $\mathbf{b}$ is the so-called bias term with N_c components that is responsible for collision treatment. It is zero for inelastic collisions and for persisting contacts i.e. when one ice feature pushes another.

The discretized system of momentum equations for the ice features can be rewritten as:

$$\mathbf{M}(\mathbf{U}_2 - \mathbf{U}_1) = \mathbf{J}^T\lambda + \mathbf{F}_{ext}\Delta t \tag{2}$$

where $\mathbf{M}$ is the inertia matrix of size $3N_b \times 3N_b$ with masses and moments of inertia at the diagonal, $\mathbf{U}_1$ and $\mathbf{U}_2$ are normal velocity vectors of size $3N_b$ on two consecutive time steps, λ is a vector containing N_c normal projections of the contact impulses that are unknown. The contact impulses are in fact momenta exchanged between bodies in contact and they must never be negative. Δt is the time step, and $\mathbf{F}_{ext}$ is the external forces and torques vector with $3N_b$ components. The external forces are continuous and may be represented by the drag forces, the Coriolis force, the added mass force, the towing force, etc. Substituting Eq. (1) in Eq. (2) will result in:

$$\mathbf{w} = \mathbf{A}\lambda + \mathbf{B} \tag{3}$$

where $\mathbf{A} = \mathbf{JM}^{-1}\mathbf{J}^T$ and $\mathbf{B} = \mathbf{JM}^{-1}\mathbf{F}_{ext}\Delta t + \mathbf{JU}_1$. When a pair of ice features is in contact the normal contact velocity $\mathbf{w}$ must be zero, so their contact impulse can be determined. Then, the velocities of the bodies are updated according to Eq. (2) using the newly found contact impulse.

The tangential projection of the contact impulse is found by applying Coulomb's friction law. The friction impulses are applied whenever tangential velocity exists; thus, no distinction is made between static and dynamic friction. The friction coefficient for ice-ice is taken from Sukhorukov and Løset (2013). For ice features that don't participate in any contact the velocities are updated according to Eq. (2) with the first term on the right side omitted.

The choice of the time step is dictated by the following factors: since the method resolves collisions in one time step, the time step should be on the order of the collision duration; on the other hand, it has to be as short as possible to avoid large overlaps between the bodies during their motion. So, it should be much shorter than a body size divided by the characteristic relative velocity.

Let us consider the choice of a time step for simulation of a model-scale experiment and a potential full-scale towing operation. Using data from Timco (2011) the collision duration (or time between the beginning of the contact and the moment the load reaches its maximum) for the model-scale is on the order of 0.1 s. In the current paper we will attempt to simulate basin-scale iceberg towing among approximately 1 m wide ice floes at 0.13 m/s, so the time step must be much smaller than 8 s. Thus, it is chosen to be as short as the collision duration which is 0.1 s.

Similarly, in full-scale the characteristic collision duration for small ice floes is under 5 s (Timco, 2011). Assuming they drift as fast as 0.5 m/s and the target size for icebreaking is 30 m, the time step must be much less than 60 s. Therefore, a time step of 5 s is acceptable.

2.2. Impulse-force conversion for collisions

When one ice feature pushes another, as, for example, when the iceberg pushes an ice floe, the contact between them persists, and the contact velocities change smoothly. In contrast, when the features collide,