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Planar multi-body model of iceberg free drift and towing in broken ice

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ABSTRACT

There are no full-scale data on iceberg towing in ice. However, there is a great interest in such an operation. Simulating the interaction between icebergs and surrounding ice floes during towing may help with choosing iceberg management strategies and design criteria for icebreakers and tug vessels. Broken ice has a discontinuous nature; therefore, it is proposed to model the interaction using a discrete element method (DEM) and known approximations of wind and water drag, wave, and Coriolis forces. The DEM is used to simulate the contacts between rigid, polygon-shaped ice floes. The floes are prevented from interpenetration by applying contact impulses tending to separate the bodies. Depending on the relative velocity of the contacting bodies, the contacts can be classified into two categories: *collisions* at non-zero relative velocity and *resting contacts* where the contacting bodies have the same velocity. Converting the calculated impulses into contact forces is straightforward for resting contacts but not for collisions. First, the applied impulses for collisions depend on the choice of restitution coefficient. Second, the collision duration must be estimated in order to convert collision impulses into forces. This paper discusses the choice of the restitution coefficient for ice and proposes an approach to estimate the collision force using the collision duration, which appears to be roughly proportional to the square root of the reduced mass. Additionally, the paper presents an innovative method to generate the ice field through which the iceberg is towed. The field is represented by a domain filled with randomly shaped rigid ice floes. The algorithm is capable of creating an ice field of given concentration and size distribution of the ice floes. The power law size distribution, obtained from aerial and satellite image analysis, is reproduced with high accuracy. The new approach to estimate the collision forces is subjected to a simple test on isolated floe impacts showing a good agreement with experimental and full-scale data. Finally, the simulation of iceberg towing is demonstrated and compared to experimental data. The results of the simulation were found to be in satisfactory agreement with the experiment.

1. Introduction

Drifting icebergs and sea ice may be a serious threat for offshore structures in the Arctic. The waters of the Greenland Sea and the Barents Sea are of high interest for the petroleum industry. But at the same time these regions are prone to icebergs and sea ice simultaneously, which may cause extreme physical loads that need to be considered during the exploitation period or even during relatively short exploratory drilling. Ice management (IM) is performed to reduce ice actions on the structure and to secure the safety of marine operations. It involves ice and iceberg intelligence, tracking, forecasting, threat evaluation, physical ice management, and possible emergency disconnection of a structure (Eik, 2008). Correct estimation of the kinematic and dynamic parameters of sea ice and iceberg drift is important for the selection of correct IM procedures (Hamilton et al., 2011).

Drift forecasting on a strategic scale provides general information about ice conditions and the presence of icebergs in the region of interest (Blunt et al., 2013). Then, several zones may be established around the structure on a tactical scale. For example, IM plans for Shtokman gas and condensate field considered short-term forecasting starting from a general surveillance zone and ending within an emergency disconnection limit (Coche et al., 2011). Alert systems are used simultaneously with a threat-evaluation tool.

Next, physical ice management such as ice breaking or iceberg towing might be performed to reduce broken ice actions or to avoid collisions with icebergs. Ice breaking and iceberg management are usually considered separately. Iceberg towing operations in open water have been successfully performed in the Canadian Arctic since 1971. The technical success, when a planned change in course was achieved, reached 85.5% for more than 1500 towing operations in open water (Rudkin et al., 2005). But iceberg towing in broken ice still hasn't been performed and it raises a great industrial interest.

There are several Arctic offshore fields where the problem of iceberg towing in ice is relevant. For example, the ice conditions presented in the Shtokman study presume icebergs in broken ice originated from

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Franz Josef Land, Svalbard, and Novaya Zemlya (Abramov, 1992). For those conditions, it may be necessary to move and deflect icebergs, e.g. by rope-towing. Ice forces during towing are a limiting factor here that mainly depends on the ice concentration, thickness, and floe size distribution.

The interaction between floating ice floes and an iceberg is a complex process that involves various physical phenomena (Fig. 1). Depending on confinement in the lateral direction, mechanical properties of the ice, speed, and floes' shapes, different failure processes may occur in the colliding ice floes. For example, highly concentrated and confined ice fields with internal stresses can undergo a ridging processes or crushing in the high-pressure zones between the floes. Also, large ice floes are likely to be split depending on several factors, e.g. the size, confinement, and shape (Lu et al., 2015).

On the contrary, low-energy collisions for unconfined sea ice lead only to minor local crushing without providing large deformations or sufficient change of the floes' shapes. Low relative velocities were measured in the Greenland Sea and no large-scale failure was observed in adjacent ice floes and no ridging around icebergs (Yulmetov et al., 2013a). Also, it was experimentally shown that towing in broken ice is feasible only at low velocity and in low concentrated ice (Eik and Marchenko, 2010). Therefore, free drift or towing of icebergs in broken ice may be modelled in two dimensions (2D).

When it comes to numerical modelling, sea ice is commonly treated as a continuum on global scales (Hibler, 1979; Hunke and Comeau, 2011). However, broken ice included into the towing model requires a discontinuous approach because the average size of an ice floe is comparable to the size of the zone of interest. Within the discontinuous approach, there are two alternative methods: the smooth discrete element method and the non-smooth discrete element method. The former describes ice as a set of bodies with a certain contact response. The material properties are given as elastic, viscous and plastic constants, and the friction coefficient. Forces are calculated explicitly for each time step of highly time-resolved contacts, providing a smooth velocity history. The method is used to model icebreakers in ice, dynamic positioning, and ridging processes (Hopkins, 1992; Løset, 1994a; Tuhkuri, 2005; Wilchinsky et al., 2011).

The non-smooth discrete element method (also called contact dynamics) is based on the so-called constraints. In addition to the momentum equation, the method deals with non-penetration constraints that must be fulfilled in order to correctly model the colliding bodies as separate. There are also friction constraints for the bodies in contact. The contact response in this case is described in terms of restitution and friction coefficients. The details of this method are given in a later section. The method was used to model ship motion in sea ice and dynamic positioning (see Konno et al., 2013; Lubbad and Løset, 2011; Metrikin and Løset, 2013). The waterline processes and large-scale failure in ice were incorporated into this method for the first time by Lubbad and Løset (2011). Their numerical model was able to reproduce ice breaking in bending after creating radial cracks in level ice, buoyancy and hydrodynamic drag forces.

Another approach in the sea-ice force estimation for iceberg motion through a field of relatively small ice floes was proposed by Marchenko et al. (2010). It was assumed that an iceberg spends its energy creating a channel in a broken ice field, by simply displacing ice floes on the sides. However, the approach provides only the average force value but not its evolution.

The paper presents a numerical model for the simulation of iceberg free drift and towing in a broken ice field using the non-smooth discrete element method. This method is capable of simulating contacts between icebergs and rigid ice floes of different shapes; this has never been done before in relation to iceberg free drift or towing in broken sea ice. In the non-smooth discrete element method, each contact is treated either as a *resting contact* or as a *collision* depending on the relative velocity of the contacting bodies. For the latter to be resolved accurately, a good estimation of a restitution coefficient is required. The restitution coefficient, in general, depends on the relative velocity of the colliding bodies and the contact geometry but it is usually treated as a material constant. This paper proposes numerical values for the restitution coefficients that should be used for iceberg drift and towing simulations. Moreover, the non-smooth discrete element method typically solves for impulses instead of forces. Estimating resting contact forces from the calculated impulses is straightforward, e.g. divide the calculated impulse by the time step. However, the estimation of collision forces is more complicated because the collision duration in reality is not the same as the time step used. A method for estimating the collision force from the collision duration is proposed in this paper. A simple test on isolated floe impacts is performed to validate our calculations of the collision duration and restitution coefficient.

In addition, the shapes of ice floes used for earlier studies evolved from circular disks to polygons, but the shapes were still predetermined and their size distribution was not considered. Ice floe size appears to be an important parameter as it affects possible failure mode and nominal contact area. The floe size distribution obtained from the nature and concentration of an ice field must be considered when generating a large number of polygonal ice floes. This paper also presents an effective method for generating a broken ice field with a given size distribution and ice concentration.

The paper is structured in a way that describes the equations of motion starting from known approximations of continuum forces. Then, it explains how to introduce discontinuity and contact dynamics, and how to calculate contact impulses. Next, the choice of the restitution coefficient value and the collision force estimation from the impulse history are discussed. Also, it is shown how to produce the initial set of random polygon shaped ice floes with a given power law size distribution. And finally, a couple of numerical examples are given. First, a simple numerical test of isolated floe impacts is carried out and compared with an experimental and full-scale dataset summarized by Timco (2011). Second, the iceberg towing with constant speed of 0.7 m/s in 50% concentrated 1.16 m thick broken ice is simulated. The average towing force calculated using the model is compared to the scaled values obtained in the experiment of Eik and Marchenko (2010).

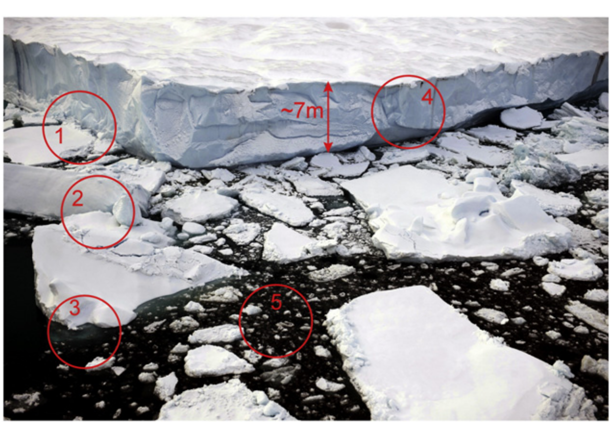

Fig. 1. An example of an iceberg drifting in broken sea ice in the Greenland Sea, 2012. Some important processes affecting the drift are: (1) ice floe–iceberg contacts, (2) floe–floe contacts, (3) water drag on floes and iceberg, (4) wind drag on floes and iceberg sail, and (5) hydrodynamic damping and brash ice.

2. Model description

Drift models usually refer to an iceberg as a point mass *M* (Bigg et al., 1997; Kubat et al., 2005; Lichey and Hellmer, 2001; Smith, 1993). In the current model, the iceberg is given a polygonal shape at the waterline. Further, it is given a sail and keel as needed for calculation of drag forces. The geometry of the underwater part can be studied using sonar (Smith and Donaldson, 1987), underwater vehicles (Hobson et al., 2011), or EM