ADVANCES IN THE SIMULATION OF SHIP NAVIGATION IN BRASH ICE

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Abstract. Brash ice is the accumulation of floating ice made up of blocks no larger than two meters across. Navigation in brash ice is becoming more usual as new navigation routes are being opened in the Artic regions. This navigation brings new concerns regarding the interaction of ice blocks with the ship. Developments are presented towards the simulation of this navigation condition including the interaction among the ship and the ice blocks. This work presents the advances in the development of a computational tool able to simulate this problem, based on the coupling of a Semi-Lagrangian Particle Finite Element Method (SL-PFEM) with a multi rigid-body dynamics tool.
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1 PROJECT OBJECTIVES

The project 'Development of new Lagrangian computational methods for ice-ship interaction problems (NICE-SHIP)' aims at developing a new generation of computational methods, based on the integration of innovative Lagrangian particle-based and finite element procedures for the analysis of the operation of a vessel in an iced sea, taking into account the different possible conditions of the ice. The computational analysis techniques to be developed in NICE-SHIP intends to improve the tools to evaluate the loads acting on the structure of a ship navigating in iced-seas and, in particular, to determine the ice resistance of the ship in different ice conditions.

This project is being developed at the International Center for Numerical Methods in Engineering (CIMNE, www.cimne.com) in Barcelona under NICOP Award N62909-16-1-2236 given by the U.S. Office of Naval Research.

The NICE-SHIP project has two main lines of research. The first one is oriented towards the modelling of the mechanics of ice [1,2,3,4,5,6], and the second one towards the simulation of navigation conditions in brash ice. In this work some details of the first line are presented, but the main focus will be on the second line.

2 MODELLING ICE MECHANICS

The constitutive structural model developed for ice first assumes an elasto-brittle material behavior of ice with a fixed yield function. The post-failure behavior of ice is modelled with a standard elasto-damage model. The model has been implemented in the context of the discrete element method (DEM). It is applied at each interface between two discrete elements (so far we have assumed spherical shapes in three-dimensional (3D) problems).

The model has been validated in the study of the multi-fracture situations of ice blocks under different loads using experimental results from the literature. The model has the necessary features to simulate the behavior of fast ice (sea ice which remain fast along the coast) and drift ice, including ice ridges (see Figures 1 and 2).

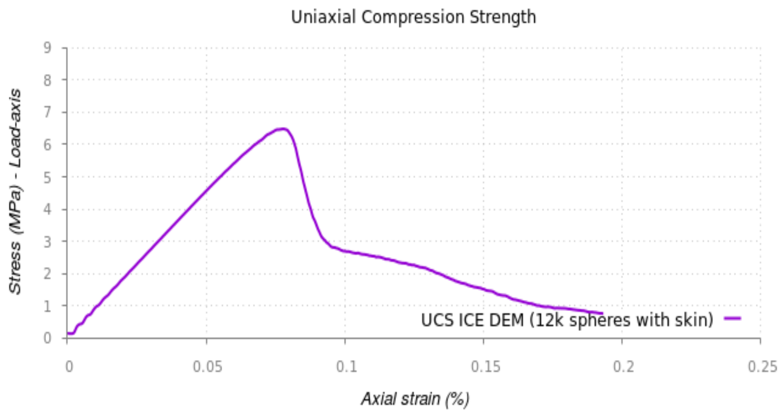


Figure 1: Axial stress-axial strain curve for a block of 7 MPa polycrystal ice under a uniaxial compression test. The straight blue line denotes the expected maximum stress Results obtained with the DEM using a mesh of 12000 spheres.

The constitutive model for ice has been tested in different scenarios that represent realistic operating situations of an ice-breaker. For this purpose, a contact algorithm has been implemented to handle ice-ship interaction. This algorithm can manage the contact between the ship and floating ice particles of sizes ranging from small particles (several decimeters, such as moderate ice blocks) and ice blocks of large size (see Figure 4).

3 NAVIGATION CONDITIONS IN BRASH ICE

3.1 Semi-Lagrangian Particle Finite Element Method (SL-PFEM)

The governing equations of the Navier Stokes equations for a Lagrangian particle are:

$$\mathrm{d}_t \boldsymbol{U}_\lambda(t) = \boldsymbol{A}_\lambda(t) = \boldsymbol{a}(\boldsymbol{X}_\lambda(t), t) \quad (1)$$

$$\mathrm{d_t}\boldsymbol{X}_\lambda(t) = \boldsymbol{U}_\lambda(t) = \boldsymbol{u}(\boldsymbol{X}_\lambda(t), t) \tag{2}$$

where t stands for time, $\mathrm{d_t}$ is the total derivative, λ is a Lagrangian particle label, $\boldsymbol{X}_\lambda(t)$ represents the position of particle λ at time t, $\boldsymbol{U}_\lambda(t)$ is the fluid velocity at $\boldsymbol{X}_\lambda(t)$ and time t, and $\boldsymbol{A}_\lambda(t)$ is the fluid acceleration at $\boldsymbol{X}_\lambda$ and time t, $\mathbf{a}(\boldsymbol{x}, t)$ is the acceleration field at position $\boldsymbol{x}$ and time t, and $\mathbf{u}(\boldsymbol{x}, t)$ is the velocity field at position $\boldsymbol{x}$ and time t. In the SL-PFEM particles carry with them only the intrinsic material and flow properties. This allows the user to insert or remove particles without affecting the extrinsic flow properties (e.g., total mass).

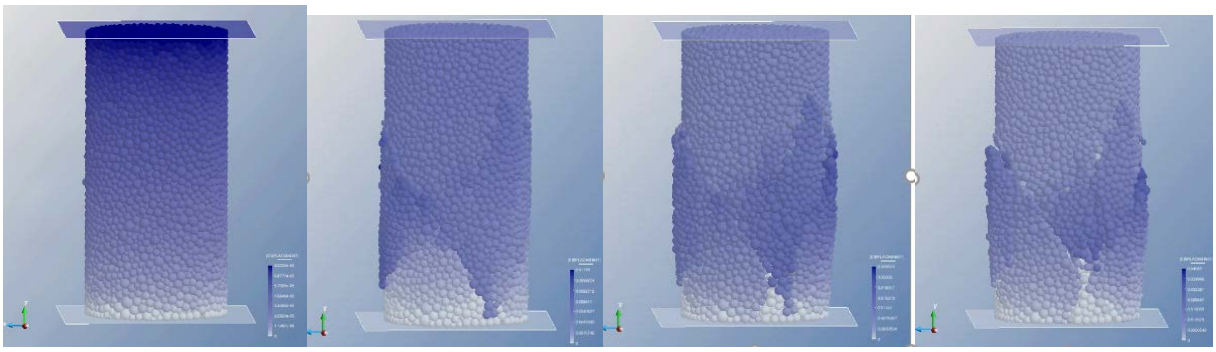


Figure 2: Snapshots of the deformation and failure of a block of 7 MPa polycrystal ice under a uniaxial compression test. Results obtained with the DEM using a mesh of 12000 spheres.

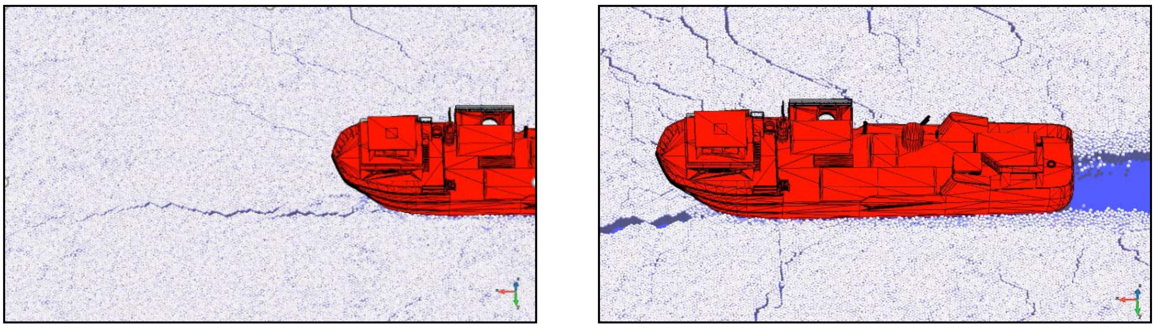


Figure 3: generic vessel. DEM results for ship-flat ice interaction analysis. Soft flat ice

When solving the incompressible Navier-Stokes equations the acceleration field is given by:

$$\boldsymbol{a}(\boldsymbol{x}, t) = -\nabla P(\boldsymbol{x}, t) + \nu\Delta\boldsymbol{u}(\boldsymbol{x}, t) + \boldsymbol{f}(\boldsymbol{x}, t) \tag{3}$$

where P is the fluid pressure divided by the fluid density, ν is the kinematic viscosity, and $\boldsymbol{f}$ is the external acceleration field.

In a pure Lagrangian framework, one needs to estimate the right hand side of Eq. (3) based on the information contain at the particles. This task face a number of challenges and is computationally expensive due to the need of searching neighbouring particles in order to estimate the corresponding derivatives.

In this work, the right hand side of Eq. (3) is estimated using the finite element method on a background mesh. Then, the integration of Eq. (1) is carried out as follows:

$$\boldsymbol{U}_\lambda(t_2) = \boldsymbol{U}_\lambda(t_1) + \int_{t_1}^{t_2} \boldsymbol{A}_\lambda(t)\,\mathrm{dt} \tag{4}$$

Eq. (4) can be split in tow equations as follows:

$$\boldsymbol{U}_\lambda^*(t_2) = \boldsymbol{U}_\lambda(t_1) \tag{5}$$

$$\boldsymbol{U}_\lambda(t_2) = \boldsymbol{U}_\lambda^*(t_2) + \int_{t_1}^{t_2} \boldsymbol{A}_\lambda(t)\,\mathrm{dt} = \boldsymbol{U}_\lambda^*(t_2) + \int_{t_1}^{t_2} \boldsymbol{a}(\boldsymbol{X}_\lambda(t), t)\,\mathrm{dt} \tag{6}$$

Eq. (5) represent a pure convection transport of momentum from position $\boldsymbol{X}_\lambda(t_1)$ to position $\boldsymbol{X}_\lambda(t_2)$. And Eq. (6) represent the increase of momentum due to the acceleration field. In order to solve Eq. (6) using the FEM on a background mesh, this must be mapped onto the FE mesh. Then a mapping operator $\boldsymbol{\mathcal{M}}^{\mathrm{h}}$ is used to map a set of particles intrinsic dependent variables $\{\Psi_\lambda\}$ onto the FE mesh $\boldsymbol{\mathcal{M}}^{\mathrm{h}}(\{\Psi_\lambda(t)\}) = \psi_h(\boldsymbol{x}, t) = \sum_a N^a(\boldsymbol{x})\psi_a(t)$, where $N^a(\boldsymbol{x})$ are the usual FE linear shape functions, a is the mesh nodes index, are ψ_a are the corresponding nodal values.

In the SL-PFEM instead of solving Eq. (6), its Eulerian counterpart is solved, which is the following Stokes type equation:

$$\begin{aligned}\boldsymbol{u}_h(\boldsymbol{x}, t_2) &= \boldsymbol{u}_h^*(\boldsymbol{x}, t_2) + \int_{t_1}^{t_2} \boldsymbol{a}_h(\boldsymbol{x}, t)\,\mathrm{dt} \\ &= \boldsymbol{u}_h^*(\boldsymbol{x}, t_2) + \int_{t_1}^{t_2} \big(-\nabla P_h(\boldsymbol{x}, t) + \nu\Delta\boldsymbol{u}_h(\boldsymbol{x}, t) + \boldsymbol{f}_h(\boldsymbol{x}, t)\big)\,\mathrm{dt}\end{aligned} \tag{7}$$

Where

$$\boldsymbol{u}_h^*(\boldsymbol{x}, t) = \boldsymbol{\mathcal{M}}^{\mathrm{h}}(\{\boldsymbol{U}_\lambda^*(t)\}) = \sum_a N^a(\boldsymbol{x})\boldsymbol{u}_a^*(t) \tag{8}$$

$N^a(\boldsymbol{x})$ are the classic FE linear shape functions, and $\psi_h(x, t) = \sum_a N^a(\boldsymbol{x})\psi_a(t)$ for any intrinsic dependent variable ψ. Once the velocity at t_2 is obtained solving Eq. (7), the velocity increase due to acceleration is interpolated and added to the particles

$$\boldsymbol{U}_\lambda(t_2) = \boldsymbol{U}_\lambda(t_1) + \boldsymbol{u}_h(\boldsymbol{X}_\lambda(t_2), t_2) - \boldsymbol{u}_h^*(\boldsymbol{X}_\lambda(t_2), t_2) \tag{9}$$

3.2 Modelling ice blocks as solid particles.

Figure 4 shows a typical condition of navigation in brash ice. In this condition, the interaction between the ship and the ice blocks results in an increased of the resistance to in still waters and in a risk of damage due to the interaction of the ice blocks with the hull and other parts such as the rudder and propellers.


Figure 4: Container ship navigating in brash ice.

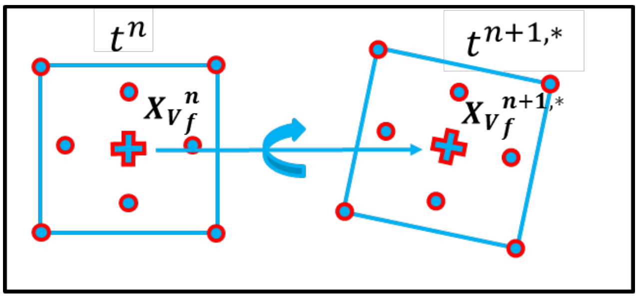
In order to take advantage of the SL-PFEM framework, the ice block is proposed to be modelled by solid particles. The main idea is to use a sort of predictor-corrector scheme within each time step. First, solid particles are treated as fluid particles, leaving the ice block to evolve as a fluid volume. Once the fluid volume trajectory is obtained, the external forces acting on its boundaries can be predicted. Second, the rigid body movement of the ice block is calculated using the predicted external forces, and imposed on the solid particles.

Implementation steps

Step 1. Solid particles are left to behave as fluid particles. Then, the ice block will evolve as a fluid volume.

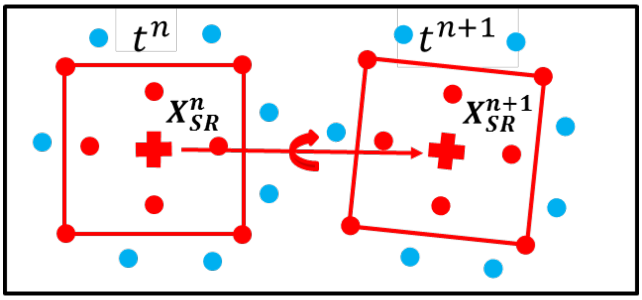
Step 2. The movement of the fluid volume can be split into three parts: translation, rotation, and deformation. The translational and rotational components are obtained by means of least squares, where it is minimized the squared error of the final position of the solid particles.

Step 3. Once the rigid body movements of the fluid volume are known, and using the integral form of the momentum equation for a fluid volume, the external forces acting on the fluid volume are predicted.



$$\boldsymbol{F}_e = \rho_f \frac{D}{Dt} \int_{V_f} \boldsymbol{u} \, dv = \rho_f V_f \frac{D\boldsymbol{U}_{V_f}}{Dt}$$

Step 4. Given the external forces on the ice block, its translation and rotation are obtained using the rigid body dynamics equations.



$$M_{SR}\frac{D\boldsymbol{U}_{SR}}{Dt} = \boldsymbol{F}_e \Rightarrow \frac{D\boldsymbol{U}_{SR}}{Dt} = \frac{\boldsymbol{F}_e}{M_{SR}} \Rightarrow \frac{D\boldsymbol{X}_{SR}}{Dt} = \boldsymbol{U}_{SR}$$

Step 5. Solid particles trajectories and velocities are imposed using the ice block translational and rotational movements.

3.1.1 Proof of concept.

The 2D flow around a circular cylinder is used as a proof of concept for the use of solid particles to model a rigid body. In this case, the cylinder moves forward with a constant velocity, so that solid particles are also enforced to move forward. Figure 2 compares the pressure field obtained using solid particles, and by imposing the body boundary conditions.

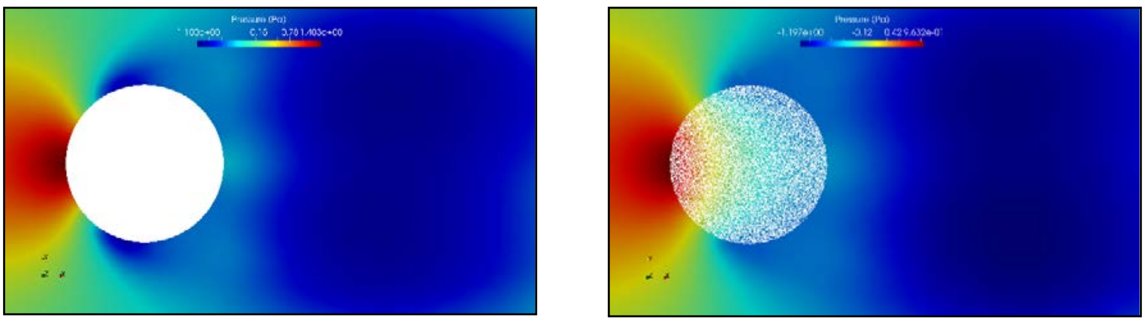


Figure 5: Pressure results for the flow around a cylinder by (Top) imposing body boundary condition and (bottom) using solid particles (solid particles are visible).

3.3 Simulating two ice blocks using solid particles.

After proving that this approach is valid when using proper mesh sizes, a simple proof of concept is proposed where two blocks of ice (one cylindrical and one polygonal) are left to move about freely in an incoming flow. See figure 3.

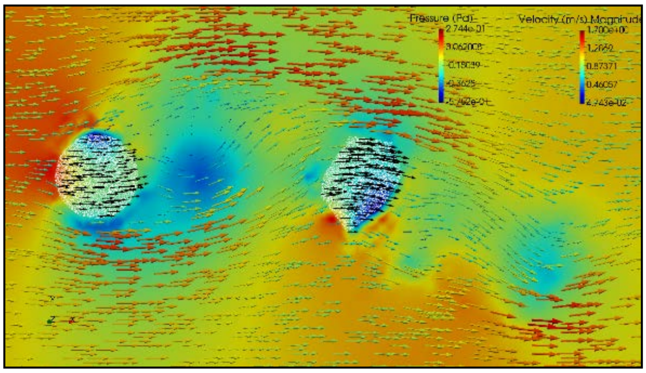


Figure 6: Simulation of two ice blocks. Pressure field over the mesh, velocity field over the fluid particles, and rigid body velocities over the solid particles.

3.4 Ice block interface enrichment (current work).

Certain problems can appear when small ice blocks are not properly defined at mesh-level. To alleviate this problem, a new method is being implemented that will better approximate this interface. This new implementation is based on an enrichment method [7] [8] where new degrees of freedom are added at mesh elements where an interface between an ice block and fluid appears. These new degrees of freedom allow to better capture the interface between the ice blocks and the fluid that surrounds it.

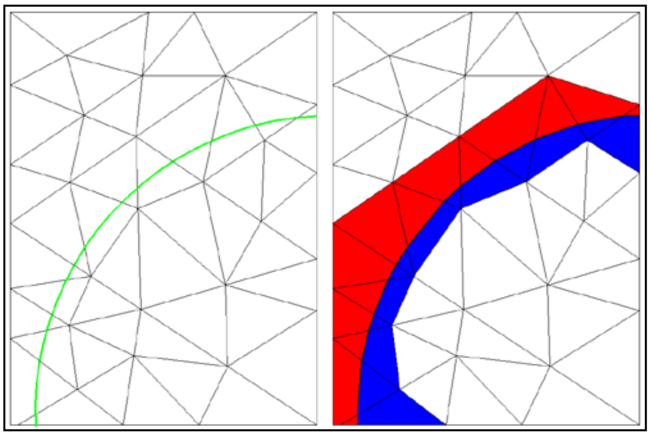


Figure 7: (left) Ice block interface over the mesh, (right) resulting enriched finite elements at the interface of the ice block.

3.5 Simulation of large number of ice blocks movements.

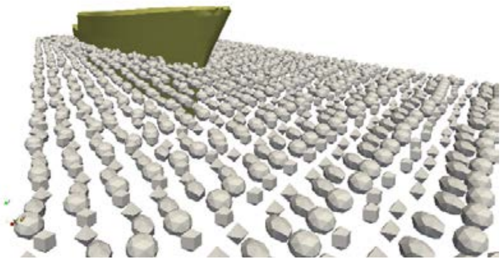
Different approaches on how to compute the interface of the ice-block with the fluid have been explained. This allows to compute with good precision how the fluid behaves around these ice-blocks and the forces that it applies to said blocks. But this is a two way problem and the movement of the aforementioned ice-blocks must be computed so that a correct estimation of the whole problem is obtained.

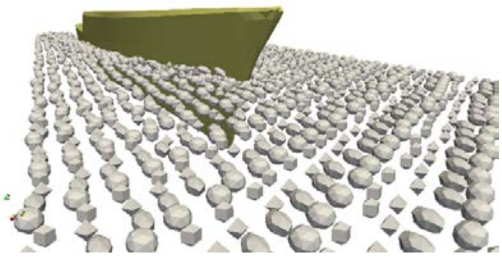
Ice-blocks will be simulated as rigid objects that are moved using rigid body dynamics. In fact, not only movements have to be taken into account, but also the possible interaction/collisions between the different objects (Not only the ice-blocks but also the ship's hull). To simplify the implementation, an external library known as "Open Dynamics Engine" or "ODE" is used [9]. This library contains two main packages: A rigid body dynamics simulation engine and a collision detection engine.

Simple example

A first approach to the rigid body dynamics library was to analyse the efficiency when analyzing a certain amount ice-blocks without taking into account the fluid-flow time. This initial problem consists of 2000 ice-blocks formed by different geometries and uniformly distributed. Throughout the simulation a ship hull geometry crosses this layer of ice-blocks provoking movements and, especially, collisions between them. Table 1 and

Table 2 provide the details of the computation and the CPU times when using a regular desktop computer. Figure 10 shows some snapshots at different simulations times.





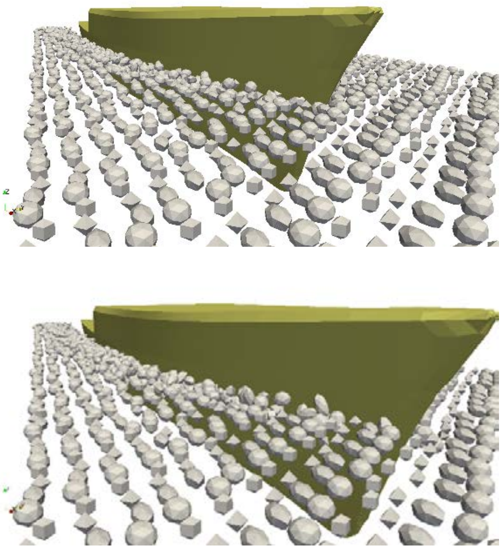


Figure 8: Snapshots a different simulation times

4 CONCLUSSIONS

Using solid particles has the advantage that the ice blocks are approximated by fluid volumes, avoiding the problem of finding its boundary and imposing the corresponding boundary conditions. But the main problem with this method is that a good enough mesh is needed to properly define small ice blocks. When the ice block is not properly reproduced at mesh-level, problems at the interface can appear and therefore give poor pressure results. One way to alleviate this problem is to enrich the mesh at the interface with additional degrees of freedom and better define said interface of the ice blocks.

Table 1: Simulation particulars

Problem Data	
Ship Mesh	30K Nodes
Ice-Block Meshes	Avg. 30 Nodes/Block
Number of Ice-Blocks	2000 blocks
Time-Step	0.01 seconds
Total Simulation	30 seconds

Table 2: CPU time

		Time (seconds)
Mesh Read		0.44
Generate Ice-Blocks		0.60
Simulation Loop	**Compute Collisions**	177.77

	Rigid Body Dynamic loop	28.59
	Output	278.55
	Total Simulation loop	492.89
Total Problem		493.92

In order to simulate a large number of ice blocks, an efficient solid dynamic solver with capabilities of simulating interactions between bodies is a must. The ODE library have shown to provide those capabilities while keeping a negligible computational time when compare to CFD times.

The combination of the ODE library with the modelling of the fluid flow around ice block using the SL-PFEM will provide a tool capable of simulating the increase of resistance in brash ice, as well as identify possible harmful interactions between the ice and the vessel.

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