



## TRA Visions 2016

**Final Project Template** – This template is to be used for submitting the final version of the project. The final deliverable should be submitted by the 30<sup>st</sup> of September 2015

Idea Number: **L1-75**

| PILLAR / TRANSPORT MODE                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
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Project Title:

Numerical simulation of ice ridge breaking



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## 1. Introduction

Increasing economic and industrial activities in Polar Regions require new engineering solutions to deal with arctic hazards. One of the main challenges for vessel navigation in ice are pressure ice ridges.

The objective of this project was to develop a numerical tool, capable of simulating the interaction process between ship hull and pressure ice ridge. The tool is based on Discrete Element Method (DEM) code developed at Hamburg Ship Model Basin to simulate ice ridges creation. The output of the program is supposed to allow visualization of ship hull/ice ridge interaction, calculate ship resistance and velocity during penetration in ice ridge, and simulate ship ramming operations corresponding to reality.

In the present project the author focuses on the following: modification of theoretical DEM algorithms in order to be adopted for ridge breaking simulation; method to introduce and to treat complex concave hull geometry with existing DEM software, taking into account adopted data structures of three-dimensional DEM; calculation of hydrostatic properties, inertial and other relevant characteristics of the ship hull (buoyancy, thrust, gravity, restoring forces); numerical integration of equations of motion of ship as discrete element in order to observe realistic performance of the vessel in an ice ridge.

The code has been validated preliminarily with corresponding experimental data, provided by Hamburg Ship Model Basin. For the current version of the project, that is being gradually developed, an extensive validation of numerical tool with existing database of model experiments should be carried out in order to check correspondence of experimental results and output of the numerical simulation.

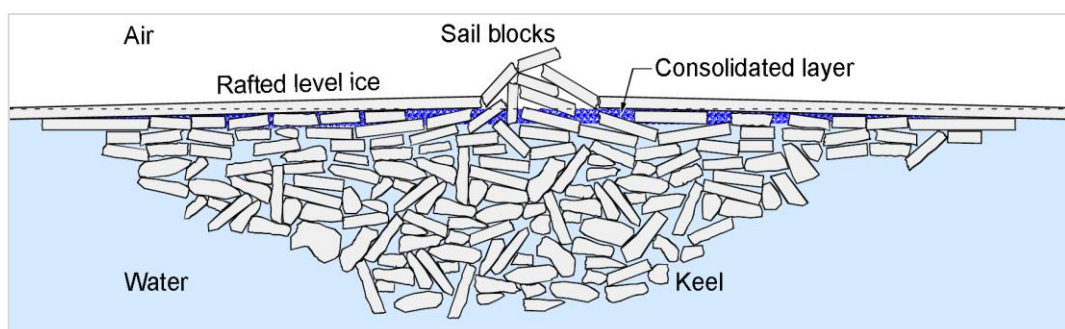
## 2. Selection of research area

Over the last few years there is a growing interest in developing the Arctic in terms of significant hydrocarbon reservoirs, ship navigation along the Northern Sea Route and various scientific researches. One of the main hazards for Arctic offshore structures and navigating ships is ice and particularly pressure ice ridges — sets of randomly oriented large pieces of sea ice along a line. These ice ridges may affect the normal exploitation of ice-going vessels, subsea pipelines, and equipment (Figure 1).



*Figure 1. Pressure ice ridges in nature*

A typical pressure ice ridge consists of the three main parts: underwater keel, above-water sail, and located in between consolidated layer (Figure 2). The keel, consisting mainly of discrete ice blocks of broken ice contributes mostly to substantial additional resistance, when ship moves through an ice ridge and very often makes ship to decelerate or even to get stuck in the ridge.



*Figure 2. Keel, sail and consolidated layer of an ice ridge*

Nowadays still the main tool available for prediction of performance and interaction of ships and structures in ice is model scale experiments in ice tanks. On the other hand, as in other scientific branches numerical methods and numerical simulations for ice-related problems are gaining more and more interest. A brief summary of advantages and disadvantages of different approaches is presented in Table 1.

*Table 1. Comparison of analytical, experimental and numerical solutions*

|                     | Models tests | Numerical simulation | Analytical methods |
|---------------------|--------------|----------------------|--------------------|
| Physical nature     | +++          | ++                   | +                  |
| Cost                | +            | ++                   | +++                |
| Ease of application | +            | ++                   | +++                |
| Accuracy            | +++          | ++                   | +                  |

Among numerical simulations the Discrete Element Method (DEM) is currently considered to be a suitable tool for modelling ice-related problems, since ice blocks could undertake large independent displacements during interaction and the ice ridge itself cannot be really represented as continuum medium. Modern commercial software, dealing with DEM, is usually available for soil mechanics, rock engineering, and simulation of particles motion. But in order these to be applied for ice problems still there is lack of physical models for ice as material.

So it can be said that there is growing demand and interest both in academic and industrial world for developing numerical simulation of ice, its various formation, and ice-structure interaction. Numerical simulation of ship breaking through an ice ridge could help to predict hull performance at early design stage without carrying out costly and time-consuming experiments, but providing more information and better accuracy comparing to available analytical solutions.

### 3. Literature Survey

Ice ridge creation, ice ridge breaking and ice ridge/structure interaction are relatively new research topics.

For numerical simulation of only ice ridge creation with Discrete Element Method there have been developed following works:

- Modelling two-dimensional ridging next to solid structures with ice rubble in the framework of «Numerical simulation of Systems of Multitudinous Polygonal Blocks» by M. Hopkins in 1992.
- A program created in the framework of master thesis «Numerical simulation of Pressure Ice Ridges» by A. Dummer in 2013. This work provides numerical simulation of ice ridge with floating up technique, implementing three-dimensional approach for ice ridge creation, based on the DEM by P. Cundall et al.
- A new version of software with floating up technique, developed at Hamburg Ship Model Basin (HSVA) in 2015, based on «Understanding the Discrete Element Method» by H.G. Matuttis and J.Chen.

Naval architects and ship designers at early design stage are mostly interested if a ship has enough capabilities to navigate in ice field, encountering ice ridges. For this issue there is existing method developed by D. Ehle at HSVA and published in the thesis «Analysis of Breaking Through Sea Ice Ridges for Development of a Prediction Method» in 2011. This work enables calculating ship's velocity and resistance during ridge breaking, taking into account the shape of the ship's hull and its power. The aforementioned method is based on available analytical formulae and results of model tests in ice tank but does not allow to provide visualization of ship behavior in the ridge and simulate different possible interaction scenarios.

As for numerical simulation of ice floes/structure interaction there are existing ongoing research projects in, for example, Norwegian Institute of Science and Technology (NTNU). These projects implement DEM simulation of such objects like floating structures and icebergs in ice floes.

There are no until so far published works on numerical simulation of ship hull breaking through an ice ridge. This project addresses this issue.

#### **4. Proposed Solution-Description of Idea**

The main idea of the project is to create software, implementing Discrete Element Method for ice blocks and to modify the available algorithm in order to be able to simulate ship breaking through an ice ridge.

As for the DEM itself, this numerical method (also called Distinct Element Method) is used for computing the motion and mutual interaction of a large number of particles. It finds application in such industries like mineral processing, powder metallurgy, rock mechanics, etc. The domain of the simulation is represented as a big number of discrete elements. The equations of translational and rotational motions of elements are solved numerically, taking into account certain kind of forces, depending on the problem studied. The output allows to find positions of elements during simulation and relevant characteristics (velocity of the flow, forces, etc.) The method can be expanded further to be coupled with Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) in order to take into account more various effects, such as deformability of discrete elements and their behavior in fluid environment.

In this project the capabilities of DEM are used for ice simulation. Since the keel of an ice ridge consists of a big number of discrete ice blocks that are normally are not frizzed together, we propose to use DEM and to adapt it in some way to consider some special characteristics of ship that would be introduced as another discrete element into domain of simulation. Thus, the ship hull would interact with ice elements of ice ridge and its behavior can be studied. The proposed algorithm of DEM considering a ship in the developed software is outlined in Figure 3.

In such a way, the proposed algorithm, under the condition being successfully implemented into software, would enable to embrace most important physical phenomena of ship breaking through an ice ridge, providing necessary information of its performance and visualization.

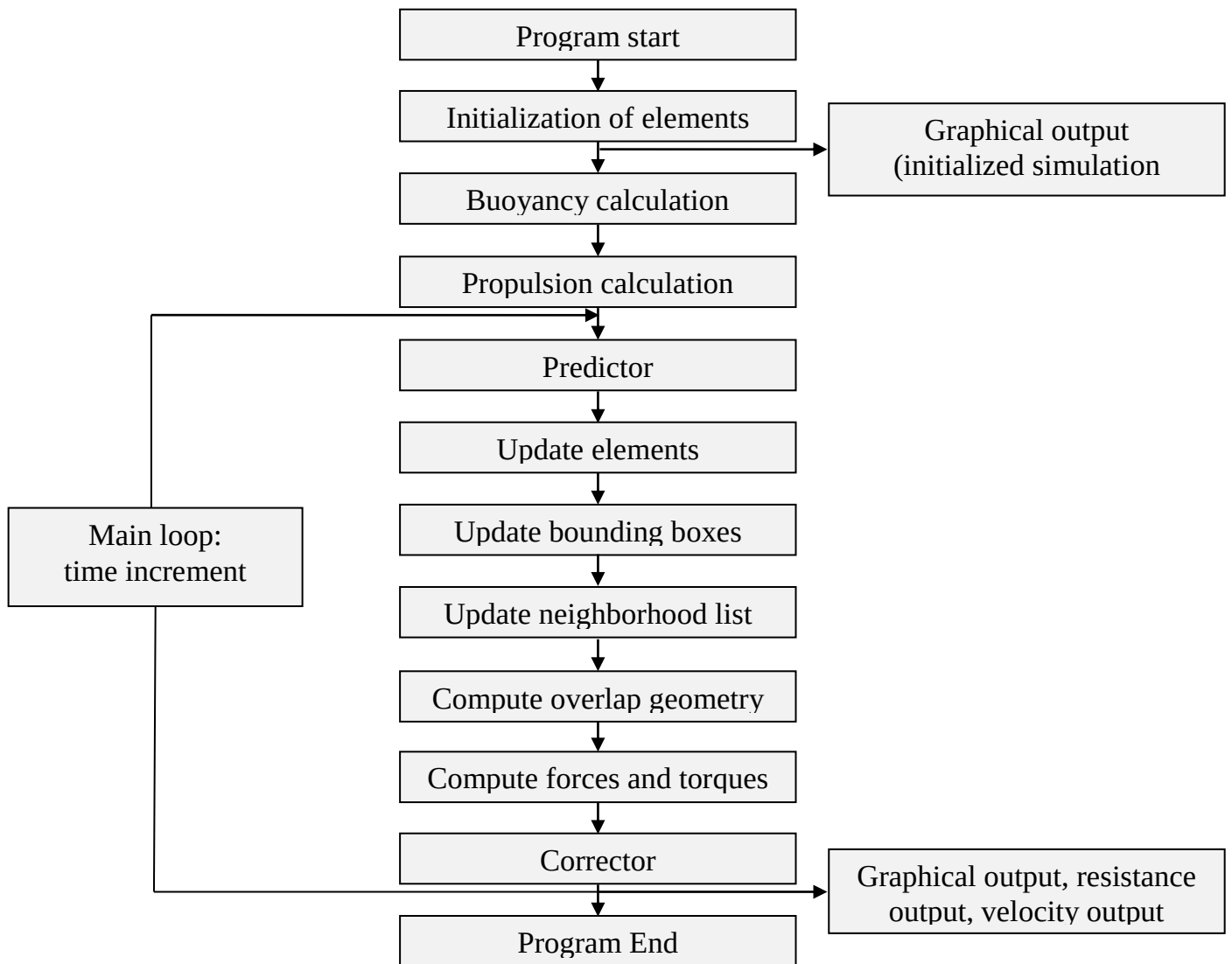


Figure 3. Algorithm of the software

## 1. Initialization of elements

In this first part prepared ice ridge must be introduced into simulation domain with number of ice elements and its positions in space (Figure 4); some important physical quantities must be defined at initialization stage (cohesion coefficient, viscous damping, friction coefficient, densities, etc.)

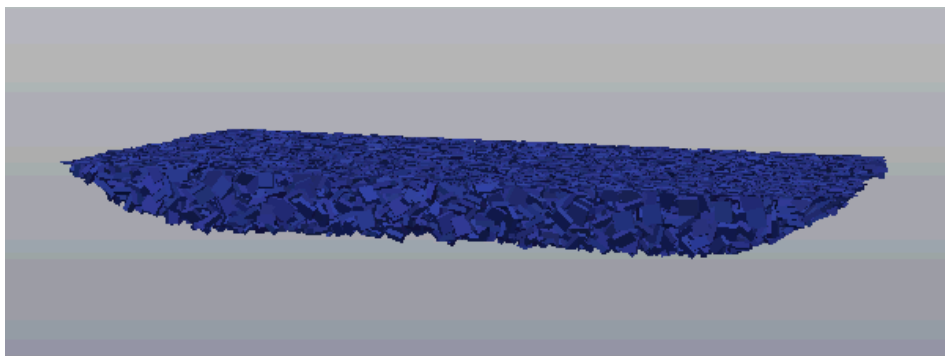
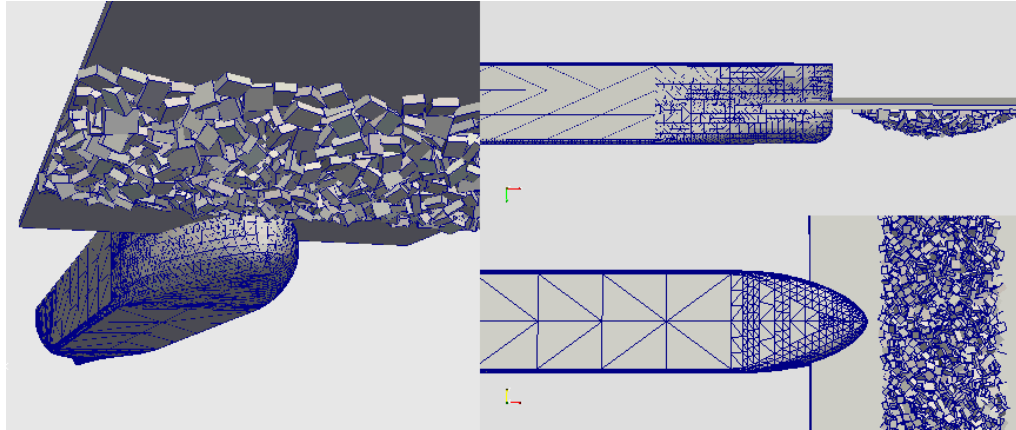


Figure 4. Input of ice ridge into simulation domain.

Moreover, since a ship hull is represented as another large discrete element, the geometry of the hull must be introduced next to the ridge (Figure 5). Hull mesh can be introduced from any relevant Computer Aided Design software (Rhinceros, etc.), using conventional file format.



*Figure 5. Ship hull mesh in simulation domain.*

## **2. Buoyancy calculation**

Initialization is followed by calculation of hydrostatic characteristics of ship hull (displacement and position of centre of buoyancy) for various drafts, heel and trim angles. Subsequently in the force computation step these quantities will be used in order to determine buoyancy force and righting moments when position of ship changes in the simulation domain.

## **3. Propulsion calculation**

Then the algorithm continues with the propulsion characteristics of ship's propeller that are introduced into simulation with a text file, taken from database of propeller tests. In the subsequent algorithm stages propeller thrust will be calculated based on current velocity of the ship using linear interpolation of introduced propeller curves.

## **4. Main loop: predictor**

During predictor step equations of ship and ice blocks motions are solved numerically based on the assumption that forces acting on discrete elements do not change. Positions and spatial orientations of elements are calculated.

#### **5. Update elements, update bounding boxes and neighborhood list.**

This steps of the algorithm update current coordinates of vertices and equations of mesh faces of discrete elements and ship hull in space. Also this part helps to define elements which might possibly be in contact during the given time step of simulation, so that computational time can be reduced by avoiding calculation of interaction between elements that cannot be in contact.

#### **6. Compute overlap geometry, forces and torques.**

Then the interactions between discrete elements are calculated and based on them forces and torques are estimated, using formulae for elastic, damping, frictional, cohesion, drag and buoyancy forces for ice elements. Apart from that displacement and buoyancy forces and thrust for ship are interpolated from predefined values, based on the current position and velocity.

#### **7. Corrector**

During corrector step translational and rotational velocities and accelerations are estimated from computed forces and torques. Based on these values new positions and spatial orientations are calculated, numerically solving equations of motions both for ice pieces and ship.

#### **8. Graphical and data output**

As the software is supposed to provide visualization of ridge breaking and necessary physical quantities regarding ship performance (first of all resistance in the ridge and velocity during breaking) these data are written in output files at certain time steps.

## **5. Address potential technology gaps**

As it can be seen from the proposed idea and from the algorithm of the developed numerical tool, the considered project can become a significant contribution to modern numerical solutions of prediction of ship performance in particular ice formation — ice ridges. Since today such numerical tools become truthful and find more and more application in the shipbuilding industry, especially for estimation of preliminary design at early stages, this project will help to answer some complex questions without organizing costly and time-consuming model experiments in ice tank.

It should be also highlighted that this project is probably the first known attempt to create numerical simulation of ship breaking through an ice ridge. In this way, this software would fill the missing link between available today, but questionable analytical formulations and reliable results of model tests in ice basins.

Apart from simulation of ice ridges, the conceptual idea of the project with implementation of the DEM can be expanded further for other ice formations, like simulation of navigation in brash ice or ice floes, both of which can be in turn represented as discrete elements. Thus the possible range of application of the software will not be restricted to only one particular type of simulation.

Taking into account the growing interest of developing Arctic and navigation along the Northern Sea Route, where ice ridges and other discrete ice formations constitute main obstacles, this project becomes quite actual for contributing into ongoing and future industrial activities.

## 6. Detailed design description

In this part of the report the key information on each step of numerical algorithm is explained in more details, providing relevant technical solutions, data, and formulae. Also main assumptions and approaches are explained and justified.

### *Simulation domain*

The simulation domain of the developed software is presented as a concept of numerical ice basin (Figure 6). All the corresponding computations during the simulations are implemented in the global reference frame.

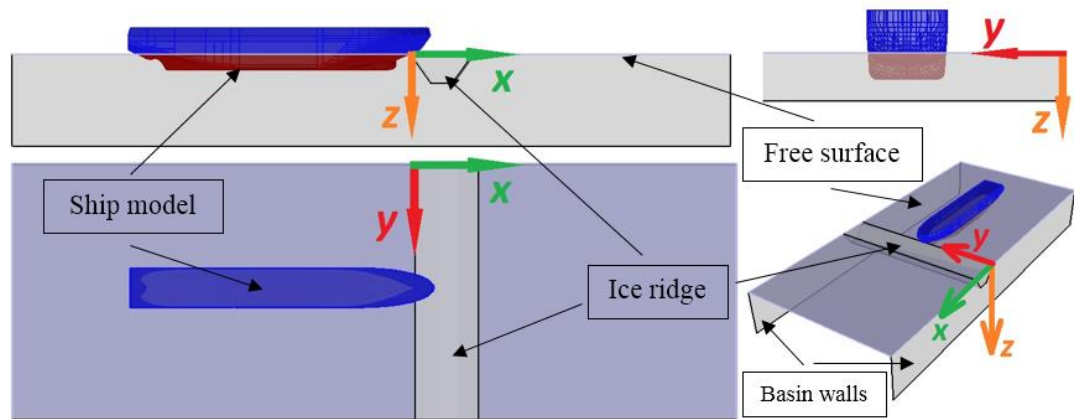


Figure 6. Simulation domain

### 1. Initialization of elements

First of all the ridge is introduced into simulation. The following parameters of the ridge are important: length and width of the ridge (RL and RW), keel width and keel height, number of elements in keel part ( $N_{ice}$ ). Together with these dimensions positions of the center of mass and spatial quaternions of each element are introduced (Figure 7).

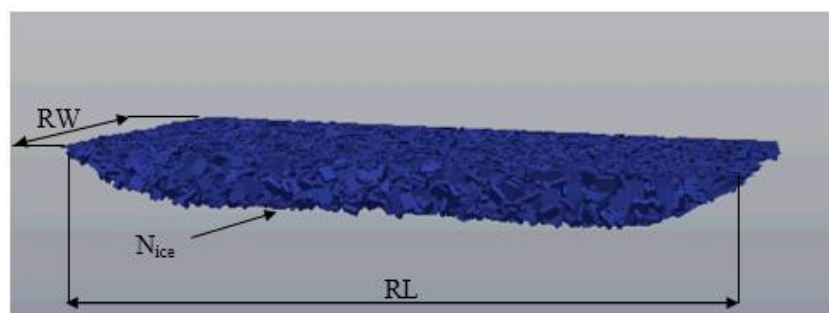
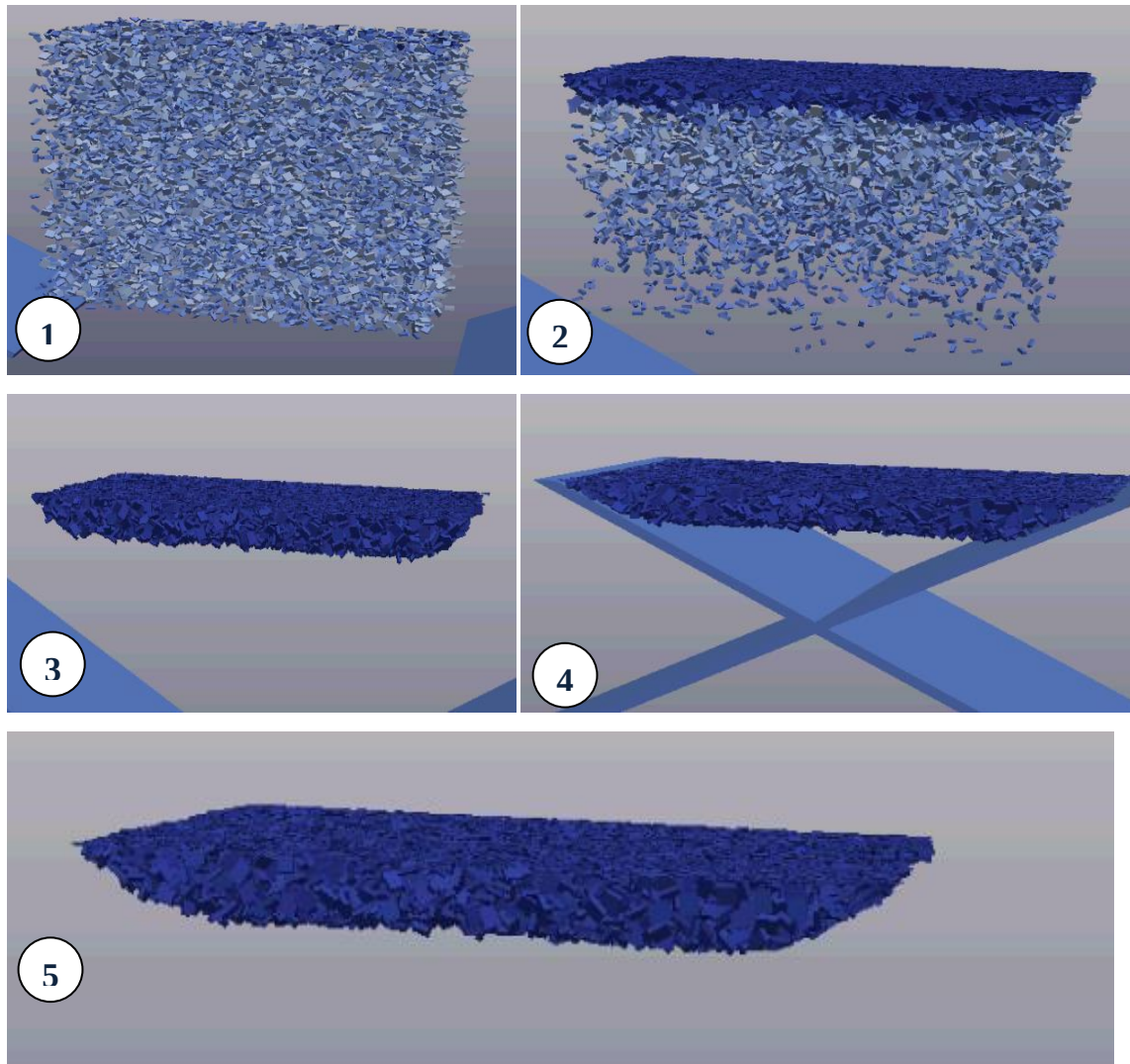


Figure 7. Dimensions of an ice ridge

Such ridge can be created, using the floating up technique of ice elements in the same software (Figure 8). This technique is implemented in five stages: 1 – initialization of ice elements randomly orientated in space, 2 – floating up of the elements due to buoyancy, 3 – preliminary shaped ice ridge, 4 – introducing pushing bars for obtaining desired shape and size of ice ridge, 5 – created ice ridge with given dimensions.

Apart from the ridge itself other important parameters are introduced at this initialization stage: friction and cohesion coefficients, coefficient of viscous damping, density and Young's modulus of ice, ridge porosity coefficient.



*Figure 8. Floating up technique for ridge creation*

Geometry of a ship hull can be introduced into simulation domain from any CAD system, supporting conventional file format for meshes ( .obj file format). For the purposes of discrete element method algorithm and effective use of data structures the hull mesh has to be triangulated (Figure 9). The software reads the input file of ship mesh and calculates necessary parameters (number of mesh faces and vertices, equations of mesh faces). Any triangular face of ship mesh is determined by its normal and distance from the origin. A normal can be defined from three vertices ( $V_1, V_2, V_3$ ) of mesh face as follows:

$$\vec{n} = \frac{(V_2 - V_1) \times (V_3 - V_1)}{\|(V_2 - V_1) \times (V_3 - V_1)\|}$$

The distance  $d$  can be solved as:

$$\vec{d} = \vec{n} \cdot V_1$$

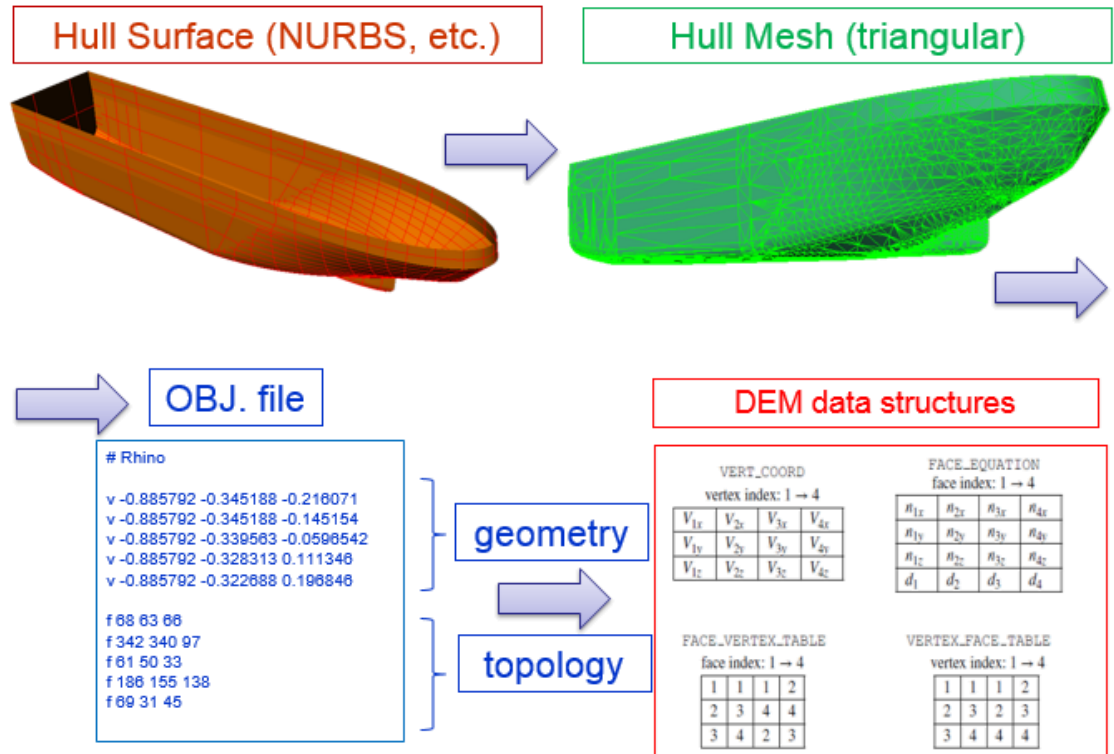


Figure 9. Introduction of ship mesh into simulation

Apart from geometry of the ship hull, other important characteristics are introduced. Among them are ship length, width, course angle, initial velocity and position relative to the ridge, displacement. Since ship hull during simulation would be exposed to different forces and torques inertial

properties of ship hull must be introduced in order to be used for rotational motion. Traditionally in ship theory, when distribution of mass along the vessel is not known at early design stage, inertia tensor can be estimated based on vessel's dimensions:

$$I_{hull} = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{bmatrix}$$

In the developed software the inertia tensor are calculated with the following statistical-imperical formulae:

$$I_{11} = 0.365MB^2$$

$$I_{22} = 0.245ML^2$$

$$I_{33} = 0.255ML^2$$

Where  $I_{11}$ ,  $I_{22}$ ,  $I_{33}$  are corresponding components of inertia tensor,  $M$  is mass of the ship,  $B$  is breadth at waterline, and  $L$  is length between perpendiculars. Other non-diagonal terms of inertia tensor are conventionally assigned to be equal zero.

## 2. Buoyancy calculation

During simulation when ship is interacting with ice ridge its position and spatial orientation might change. From the experiments it is known that ship's draft and trim angle can change slightly due to significant buoyancy force  $F_{bk}$  of ice rubble in the keel part of the ridge (Figure 10). In reality when these parameters are changed corresponding restoring buoyancy forces  $\Delta F_b$  and moments must appear. Thus in the simulation such forces and moments should also be taken into account.

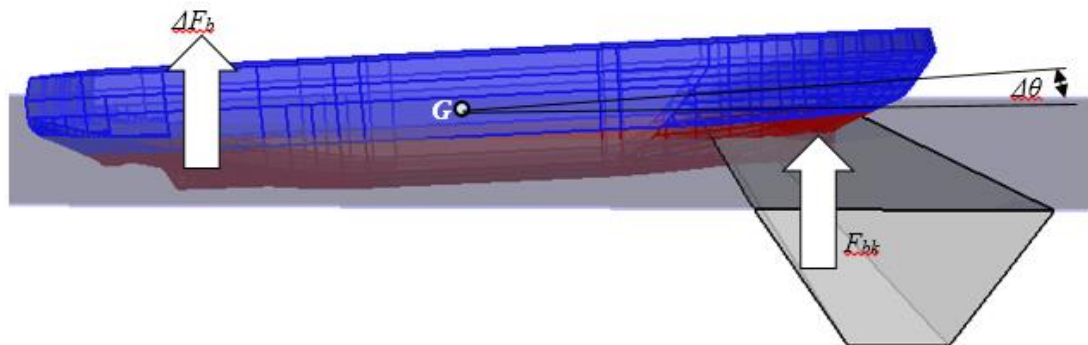


Figure 10. Change of bow draft and pitch angle

In this part of the algorithm precalculation of displacement and position of center of buoyancy for different ship drafts, heel and trim angles is implemented (Figure 11).

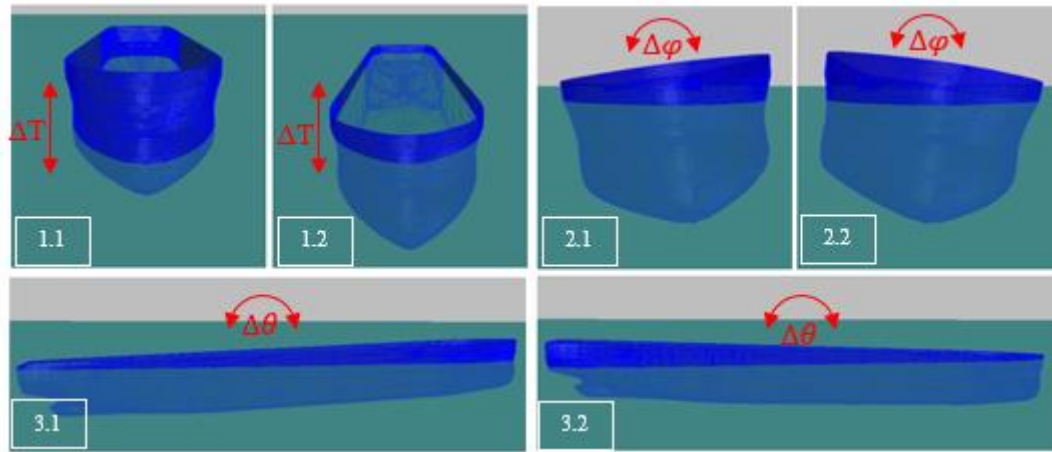


Figure 11. Precalculation of buoyancy for various conditions

In order to save calculation time during simulation, buoyancy is calculated before entering main loop. During execution of the algorithm current values of displacements and position of centre of buoyancy are interpolated from these precalculated values. Thus, in order to get reasonable precision of buoyancy force and righting moments a suitable range of expected drafts, heel and trim angles must be chosen.

For the given combination of draft, trim and heel angles displacement can be calculated, dividing underwater hull into certain number of cross sections and integrating the area of each section along the length of waterline (Figure 12).

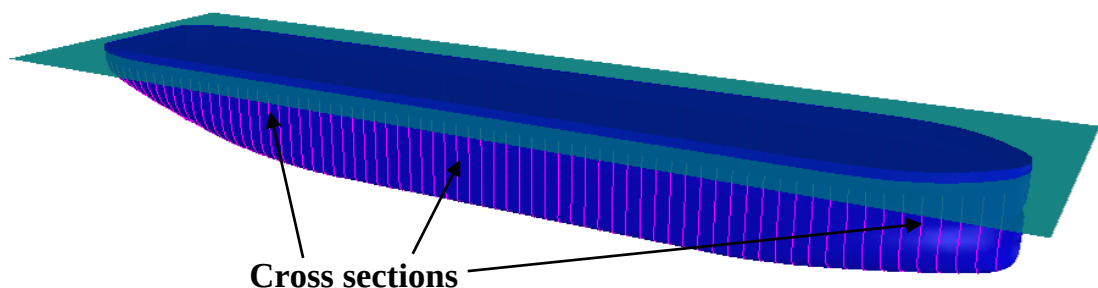


Figure 12. Cross sections of underwater hull

Each single cross sectional area is calculated, using computational geometry algorithms. In this buoyancy module algorithm of meshes intersections is used to obtain coordinates of points of hull mesh intersection with vertical plane of given cross section. After obtaining contour points (Figure 13) of section a gift wrapping algorithm is used in order to get the contour line.

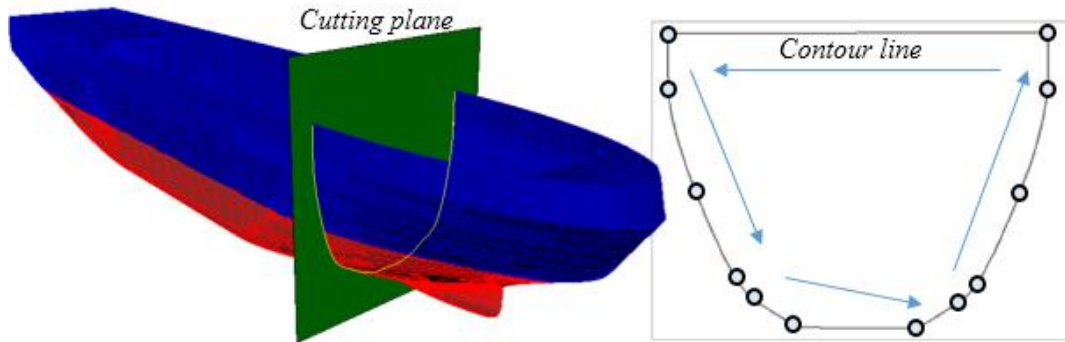


Figure 13. Contour points of section

Subsequently each of the contour line is divided into triangles and area of each triangle A in the cross section can be calculated, using properties of cross product of two vectors  $\overrightarrow{V_1V_2}$  and  $\overrightarrow{V_2V_3}$  (Figure 14):

$$A = \frac{\overrightarrow{V_1V_2} \times \overrightarrow{V_2V_3}}{2}$$

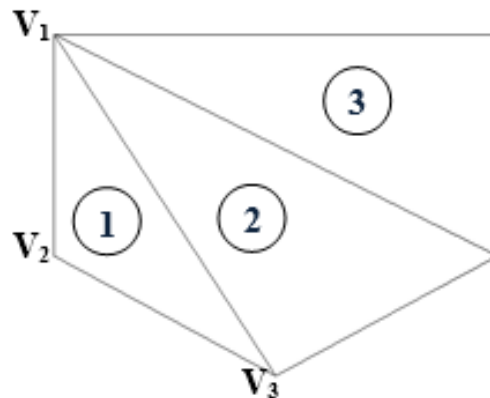


Figure 14. Example of contour triangulation

Provided all the cross sectional areas are calculated, the displacement of ship for given draft, trim and heel can be defined as integral of sectional areas. In this software self-written Simpson's integrator for calculating displacement is used.

### 3. Propulsion calculation

At this stage of the algorithm propeller characteristics are introduced into simulation (Figure 15). These values are read from propeller input file and will be used during forces computation for determining thrust by interpolating the value of thrust coefficient  $K_t$  for a given revolutions (RPM) value and depending on current velocity of ship in the ridge.

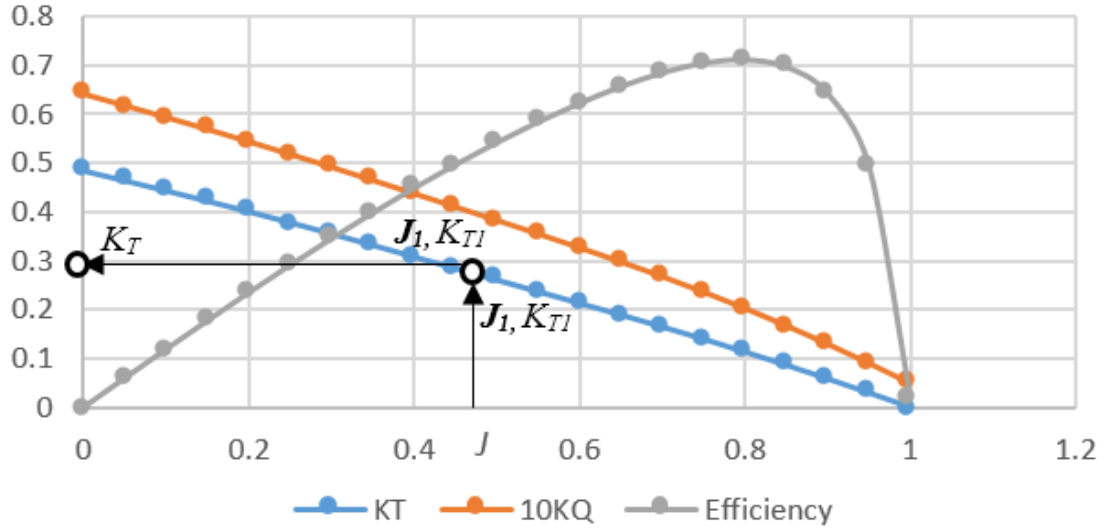


Figure 15. Typical propeller curve

### 4. Main loop: predictor

For all ice elements and ship hull during simulation time the next equations of translational and rotational motions are solved:

$$m \frac{d^2 r}{dt^2} = \Sigma F_i$$

$$\frac{d^2 q}{dt^2} = \frac{1}{2} (\dot{\omega} q + \dot{q} \omega)$$

In these equations  $m$  is mass of an element,  $r$  is a position of center of mass of element in space,  $t$  is time,  $F_i$  are different kinds of forces applied to the elements,  $q$  is element quaternion (describing spatial orientation of an element),  $\omega$  is angular velocity of rotation.

During the predictor step we increment time with time step  $dt$  and estimate the new values of  $r$  and  $q$  for all discrete elements, assuming there are no changes in forces and torques acting on them:

$$r = r + \dot{r}dt + \ddot{r}\frac{dt^2}{2}$$

$$\dot{r} = \dot{r} + \ddot{r}dt$$

$$q = q + \dot{q}dt + \ddot{q}\frac{dt^2}{2}$$

$$\dot{q} = \dot{q} + \ddot{q}dt$$

## 5. Update elements, bounding boxes and neighborhood list.

After predicted positions  $r$  and spatial orientations  $q$  of centers of gravities are defined, coordinates of all the vertices of elements and position of ship mesh  $r_i$  must be recalculated in simulation domain using properties of quaternions as follows ( $q^*$  is a quaternion conjugate of  $q$ ):

$$r_i = r + qrq^*$$

Then bounding boxes of all discrete elements are recomputed. These bounding boxes help to understand if the elements that are close to each other at a given time step could have contact with each other. From the Figure 16 an example of possible mutual orientation of elements and their bounding boxes is presented.

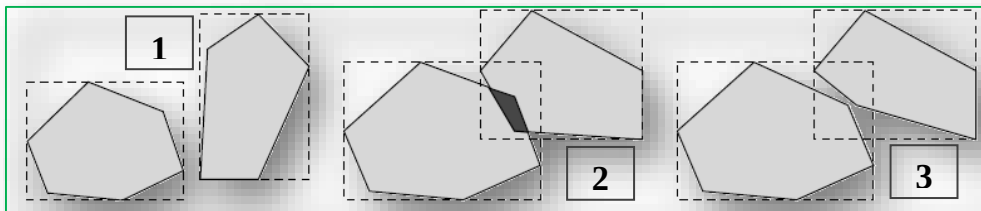
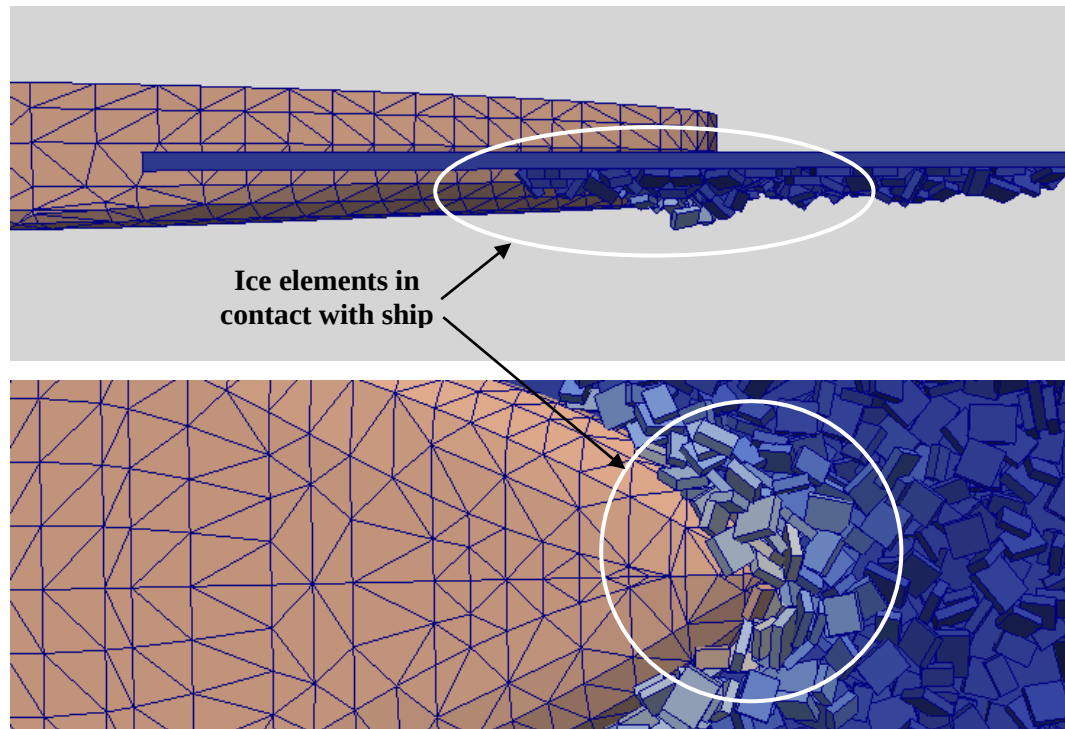


Figure 16. Bounding boxes example for two neighbour elements

In the first case bounding boxes are not intersecting and hence the elements themselves are not in contact. In the second and third cases bounding boxes are intersecting, but the contact between elements is present only in case 2. This simple approach, being a part of the so-called ‘Sort and Sweep’ algorithm enables to decrease computational time significantly during simulation.

## 6. Compute overlap geometry, forces and torques.

For elements that are possibly in contact with each other (ice/ice, ice/hull - Figure 17) the computation of overlap polyhedron is implemented, using algorithms of computational geometry.



*Figure 17. Ice elements in contact with ship hull*

For each pair of intersecting elements the overlap geometry between them is computed in the following stages:

- Computation of inherited vertices (originally belonging to elements vertices)
- Computation of generated vertices (created due to intersection of mesh faces vertices)
- Computation of faces of overlap polyhedron
- Computation of contact area and direction of contact force

An example of overlap between two ice elements is outlined in the Figure 18.

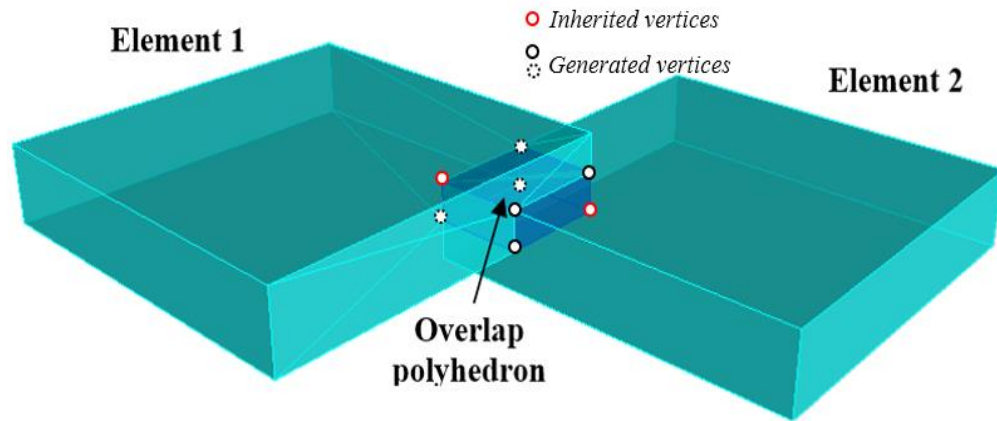


Figure 18. Overlap polyhedron between two ice elements

Afterwards elastic forces and torques are calculated, based on the overlap geometry. These forces contribute mostly to make ice blocks to move and to decelerate the ship hull during breaking the ice ridge. Apart from them other types of forces and torques are computed for ice elements and for ship hull. The list of forces and torques, computed and applied for ice and ship are presented in (Table 2).

Table 2. Forces and torques applied to elements

| Force                | Torque <sup>1</sup> | Application | Direction       |
|----------------------|---------------------|-------------|-----------------|
| Elastic              | +                   | Ice/Ship    | Normal          |
| Damping              | +                   | Ice/Ship    | Normal          |
| Friction             | +                   | Ice/Ship    | Tangential      |
| Dissipation          | +                   | Ice/Ship    | Tangential      |
| Cohesion             | +                   | Ice         | Normal          |
| Viscous Drag         | +                   | Ice         | Velocity vector |
| Buoyancy             | +<br>(couple)       | Ice/Ship    | Upwards         |
| Gravity              |                     | Ice/Ship    | Downwards       |
| Propeller Thrust     | -                   | Ship        | Horizontal      |
| Level Ice Resistance | -                   | Ship        | Horizontal      |

<sup>1</sup> + means the force creates torque  
 - means the forces creates no torque

## 7. Corrector

The corrector step acts on the predicted coordinates after the forces and torques at given time step are evaluated. The equations of translational and rotational motions are solved again with correction coefficients, that can be found in relevant literature on predictor-corrector solvers, are equal  $c_0 = 0$ ,  $c_1 = 0.5dt$  and  $c_2 = 1$ .

Equations of translational motions:

$$\begin{aligned}\ddot{r}_t &= \frac{F}{m} \\ \Delta \ddot{r} &= \ddot{r}_t - \ddot{r} \\ r &= r + c_0 \Delta \ddot{r} \\ \dot{r} &= \dot{r} + c_1 \Delta \ddot{r} \\ \ddot{r} &= \ddot{r} + c_2 \Delta \ddot{r}\end{aligned}$$

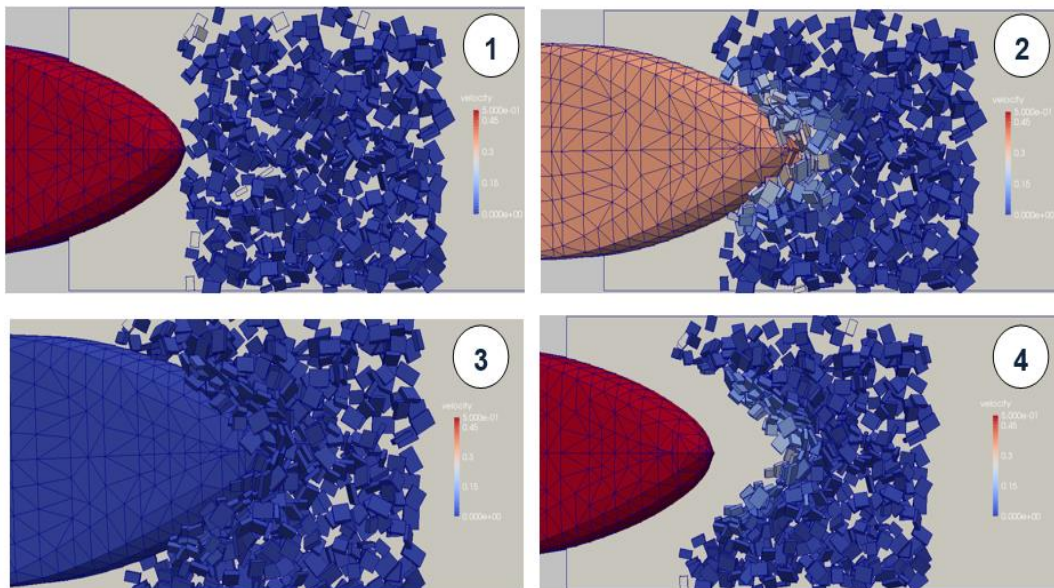
Equations of rotational motions:

$$\begin{aligned}I &= A I^b A^T \\ \omega &= 2 \dot{q} q^* \\ L &= I \omega \\ \dot{\omega} &= J^{-1} (L \times \omega + \tau) \\ \ddot{q}_t &= \frac{1}{2} (\dot{\omega} q + \dot{q} \omega) \\ \Delta \ddot{q} &= \ddot{q}_t - \ddot{q} \\ q &= q + c_0 \Delta \ddot{q} \\ \dot{q} &= \dot{q} + c_1 \Delta \ddot{q} \\ \ddot{q} &= \ddot{q} + c_2 \Delta \ddot{q}\end{aligned}$$

In these equations the terms are computed based on the values of computed previously forces and torques. In the aforementioned formulae we introduced the following notations:  $\ddot{r}_t$  – translational acceleration at current time step,  $\Delta \ddot{r}$  – change of translational acceleration from previous to current time step,  $I$  – inertia tensor in space-fixed coordinate system,  $I^b$  – inertia tensor in body-fixed coordinate system,  $A$  – rotation matrix,  $L$  – rotational momentum,  $\tau$  – torque,  $\ddot{q}_t$  – quaternion acceleration at current time step,  $\Delta \ddot{q}$  – change of quaternion acceleration from previous to current time step.

## 8. Graphical and data output

At certain time steps the data on ship mesh and positions of ice elements of ridge are written in graphical output files. Together with positions of discrete elements their velocities are written. This allows to create visualization of ridge breaking process, using computer graphics software. An example of different stages of a ship breaking through ice ridge is presented in the Figure 19.



*Figure 19. Example of ridge breaking visualization*

At stage 1 the ship has maximum velocity before entering ice ridge. At the second stage it can be seen that ship is penetrating in the ridge and its velocity decreases rapidly. At stage 3 the hull gets stuck in the ridge and the velocity of the ship is close to zero. At the final stage 4 the new attempt to break through the ice ridge is starting and ship again has maximum velocity. Depending on the ship inertia, maximum velocity and thrust value there might be necessary to make several such attempts to break through the ridge. This process is called ‘ramming’ and used mostly in navigation to break through an ice ridge.

## **7. General conclusions on the project**

The purpose of the present thesis was to develop a numerical tool, capable of simulating the process of ship breaking through an ice ridge. This goal has been successfully achieved by creating a software in FORTRAN programming language. This software became the first known attempt to apply numerical simulation for ice ridge breaking.

The numerical solver is based on implementation of Discrete Element Method representing a ship hull as a set of convex discrete elements. The software has been designed in such way, so that visualization of ship breaking through an ice ridge is the main output of the program. Apart from that, all the relevant parameters of ridge and hull interaction can be exported. Such parameters are ship position and orientation, velocity and acceleration, thrust, etc. The software provides high flexibility in terms of modelling different interaction configurations and initial conditions such as: dimensions of the ridge, ship's velocity, position and orientation before breaking, parameters of forces calculation, etc.

Significant attention has been drawn on how to implement the ship hull as floating body in DEM simulation. For this some computational algorithms, vector algebra and numerical integrators have been used in order to estimate buoyancy characteristics of the hull. The concept of pre-calculated buoyancy table has been introduced in order to save computational resources during time integration of ridge breaking.

The validation of the numerical simulation with experimental data has been carried out. Discussions and suggestions of the obtained results have been provided for future calibration of the model. In general it can be said that more in-depth validation is required and the software and forces calculation need to be tuned in order to get precise solutions.

## 8. Source of additional information used & Appendices

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