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Ship propagation through ice field

Juri Kajaste-Rudnitski and Pentti Kujala[1]

Summary. Ships navigate often on the ice covered waters of the Baltic Sea independently without ice breaker convoy. At first, ship bow enters into contact with the edge of ice field, then penetrates into ice by breaking the ice edge and propagates further through ice field. During the breaking process ice sheet exerts contact pressure onto ship hull obstructing thus its propagation. When a ship moves straight forward the contact area is relatively small and does not exceed ship width. When a ship turns within ice sheet its whole side runs into ice and contact area rises. This process is studied numerically in this paper. Ship hull is presented as a rigid body with its mass concentrated at its centre of gravity. Ship movements in space are also defined by three degrees of freedom at this point. Ice sheet is modelled as a thin deformable shell with modified Drucker-Prager material model assigned to ice. When shear strain in an element reaches a certain level this element fails and is removed from the finite element mesh. Contact pressure along the ship hull due to ice is integrated to the centre of gravity of ship hull in the form of resultant forces and moments. It is shown that ice breaking is a random process and time history of reaction forces presents a series of high peaks of very short duration. It is shown whether the ship can overcome ice field resistance with given mass and velocity or will the ship stop in ice. Frequency of major ice force peaks depends on velocity of the ship propagation: the greater the velocity, the greater the frequency.

Key words: ship, ice-breaking, numerical simulation, finite element modelling

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Introduction

The ice induced loads are initiated due to the relative movement between the ship and ice. Therefore the mathematical modelling of this process has to include the motions of the ship, modelling the ship-ice interaction and possible movements of the ice floes impacted by the ship. There are basically three main approaches than can be used in the development of the formulations: a) direct numerical time integration based simulation of the ice-breaking process, b) analyzing the forces during the ice impact process by energy methods and c) semi-empirical methods utilizing the measured full scale data of ice induced loads.

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Numerical methods will be only considered here. Numerical approach will solve on a specified time steps the differential equations of ship motions when a varying force is applied on the hull due to the ship-ice interaction. This has been done by the finite element approach earlier by Valanto [1] and by developing numerical simulation models including the ship manoeuvres and ship hull-ice interaction, where the ship hull interaction is partly modelled by empirical data, see e.g. Su [2]. The empirical data is needed to calculate the ice-breaking process and especially to calculate the typical piece sizes broken from the ice so that the real contact between the ship hull and ice can be monitored during the simulation. This means that in this case the ice strength is the determining factor for the maximum load.

The ice-breaking process is studied numerically in this paper by defining ship movements with three degrees of freedom and by modelling ice sheet as a thin deformable shell with modified Drucker-Prager material model in ABAQUS assigned to ice. When the maximum shear strain in an element reaches certain level this element fails and is removed from the finite element mesh. This approach to use shear failure is new in this context and enables detailed detail modelling of the contact pressures along the ship hull. The numerical approach is applied on a 23700 DWT container carrier moving in level ice.

Problem definition and modelling principles

Figure 1 illustrates the process of ice-breaking and the possible contact forces affecting ship during this process. Typically when going straight ahead ship bow will break the ice and thereafter the ship-ice interaction and forces due this interaction vary a lot along the ship hull. The analysis of this process is studied numerically in this paper. To simplify the analysis, it is assumed that the ship has a constant speed forwards and when she starts to turn also the angular velocity during the turning is constant. The model does not include water and, consequently, there is no buoyancy forces acting on the hull. Due to this shortcoming only 3 degree of freedom of ship movement are allowed – surge (x), sway (y) and yaw (ϕ). The origin of the coordinate axis is located at the center of gravity of the ship, as shown in Figure 1.

When ship moves straight forward its local coordinate system with origin at the centre of gravity coincides with the global coordinates. Constant velocity or displacement at every time moment in global x-axis direction (surge) is given as a boundary condition. Other movements are not allowed. When ship turns around vertical z-axis its local x-axis and y-axis are not the same as the global ones. Vertical z-axis is the same for both systems. Constant velocity along local x-axis remains always the same but its projections onto global x- and y-axis should be given as well as rotation velocity around z-axis. Container carrier used is shown in Figure 2, it is 150 m long, 28 m wide and the capacity is 23700 DWT. 3D model of the surface of the ship is needed as this will determine the contacts between ship and ice, which in the calculation procedure from the boundary conditions for the FE- model of the ice surface. So these boundary conditions are moving as a function of ship movements as described next.

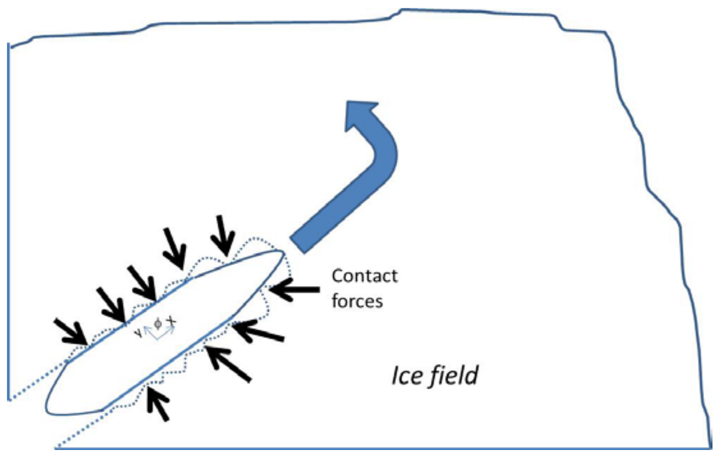


Figure 1. Illustration of the ice-breaking process and forces affecting ship when navigating in ice.

As it is mentioned above ship hull is presented as a rigid body (Figure 2). Material Druker-Prager model is assigned for ice. When shear strain in an element reaches certain level this element fails based on this failure criterion and is removed from the finite element mesh. Druker-Prager model is used for materials where compressive yield strength is greater than tensile one. For ice, typically the tensile strength can be only about 50 % of the compressive strength [3]. In addition, during the ice crushing process, local shear failure is the dominating failure mode, see e.g. Daley [4]. The yield criterion is based on the shape of the yield surface and has a linear form, see Figure 3.

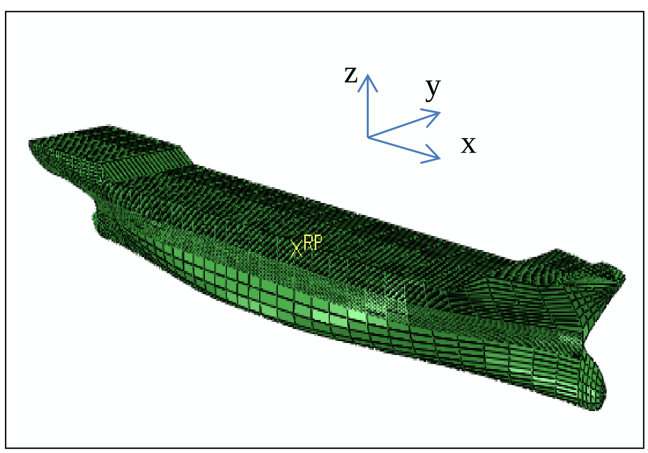


Figure 2. Container carrier. The origin of the coordinate system is located in the center of gravity of the ship model.

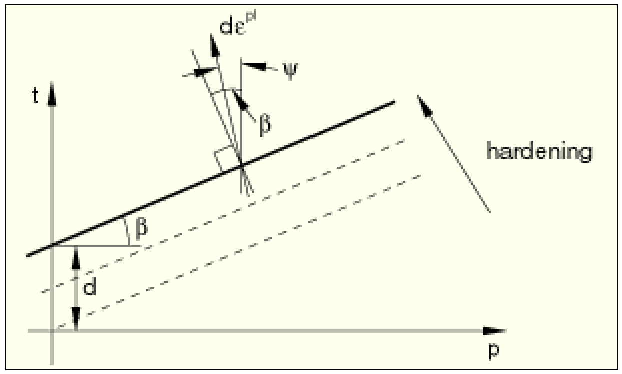


Figure 3. Linear Drucker-Prager model: yield surface and flow direction in the p–t plane.

The modified Drucker-Prager plasticity model in Abaqus enables a possible noncircular yield surface in a general deviatoric plane to match different yield values in tension and compression. It allows also the separation of dilatation and friction angles. Linear Drucker-Prager criterion is written in terms of the three stress invariants and looks as follows (assuming $K=1$):

$$F = t - p \cdot tan\beta - d = 0 \tag{1}$$

where

$$t = \frac{1}{2} q \left[1 + \frac{1}{K} - (1 - \frac{1}{K})(\frac{r}{q})^3 \right],$$

β is a material friction angle in the *p-t* stress plane, d is a material cohesion, K is the a ratio of the triaxial yield stress in tension to the triaxial yield stress in compression, p is an equivalent pressure stress, as $p = 1/3 I_1$, q is a von Mises equivalent stress: $q = (3/2\ s_{ij}s_{ji})^{1/3}$ and $r = (9/2 s_{ij}s_{jk}s_{ki})^{1/8}$. Here S is a stress deviator. Ψ is a dilatation angle in the *p–t* plane. For details see Chen and Han [5].

For actual ice material Drucker-Prager parameters are given as input data: material friction angle $\beta = 50^o$, dilatation angle $\psi = 45^o$ and $K = 0.8$ [3,6,7]. Hardening parameters are: yield stress 4.0 MPa and 5.0 MPa when strain is 0 and 0.5 respectively. Elastic modulus, $E = 8\ GPa$, Poisson ratio $\nu = 0.34$ and density 920 kg/m^3 [3]. Used ice thickness is 0.2 m.

Shear failure model is based on the equivalent plastic strain, which in its turn defines a damage parameter

$$\omega = (\epsilon_o^{pl} + \sum \Delta\varepsilon^{pl})/\varepsilon_f^{pl} \tag{2}$$

If ω> 1, failure occurs. Here ε_o^{pl} is an initial value of equivalent plastic strain, $\Delta\varepsilon^{pl}$ is an increment of equivalent plastic strain and $\varepsilon^{pl}{}_f$ is the a failure strain. Equivalent plastic failure strain $\varepsilon^{pl}{}_f$ is given as input data. Note that the equivalent plastic strain corresponds to the von Mises stress criterion and is defined as:

$$\varepsilon_0^{pl} + \int_0^t (\sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{pl}\ \dot{\varepsilon}_{ji}^{pl}})dt \qquad (3)$$

When the shear failure criterion is met all stress components are set to zero and the failed element is removed from the mesh. The shear damage initiation criterion is used in the model for predicting the onset of damage due to shear band localization. The model assumes that the equivalent plastic strain at the onset of damage is a function of the shear stress ratio and strain rate.

The following input data are needed. Equivalent fracture strain at damage initiation is $\varepsilon_o^{pl} = 0.001$. The shear stress ratio is defined as:

$$\theta_s = (q + k_s \cdot p)/\tau_{max} \qquad (4)$$

where q is the von Mises equivalent stress, p is the pressure stress, and τ_{max} is the maximum shear stress and $\tau_{max} = 0.5\ MPa$. The equivalent plastic strain rate $\xi^{pl} = 0.5\ 1/s$.

Solution strategy

ABAQUS/Explicit option is used to perform a dynamic analysis. The explicit dynamic procedure deals with a large number of small time increments. An explicit central difference integration rule is used. The explicit central difference operator satisfies the dynamic equilibrium equations at the beginning of the increment t, the accelerations at the time t are used to advance the velocity solution to time $t + \Delta t/2$ and the displacement solution to time $t + \Delta t$.

The central difference operator is conditionally stable. The approximation to the stability limit of the operator is defined as the smallest transit time of a dilatational wave across any element in the mesh $\Delta t = L_{min}/c$, where L_{min} is the smallest element dimension and c is a dilatational wave speed in the material. Another estimation of the stability limit is given in terms of highest frequency of the system as $\Delta t \leq 2/\omega_{max}$.

The actual automatic time incrementation algorithm uses both these estimations when default option is requested. The use of small increments defined by stability limits is advantageous since it allows the solution to proceed without iterations and without requiring tangent stiffness matrices to be formed.

The large number of time increments (about one million in some cases) during entire analysis step poses some problems when boundary conditions for surge, sway and yaw are defined. For straight moving ship only surge degree of freedom is active and constant velocity is given to the ship in this x-direction (local and global). That is at time $t=0$ ship movement $l=0$ and at the end of analysis $t=T$ the ship travels the distance $l=D$. Ship movement at automatic time increment Δt will be $\Delta l=D*\Delta t/T$. This input data may be given in the form of table of two rows: time and displacement values at the beginning and end of the analysis.

Quite a different situation occurs when ship turns around its (local and global) vertical z-axis. Velocity of the ship along its local x-axis V m/s remains the same during the whole process of propagation. Total time consists of two parts: time of straight movement and time of rotation $T=T_{straight}+T_{rot}$. During rotation time $(T_{straight} > t \geq T_{rot})$ the ship turns on 90^o with angular velocity φ ^{o}/s. At time increment Δt_i angular velocity will be $\Delta\varphi_i = 90^o*\Delta t_i/T_{rot}$. Now all three boundary conditions (surge, sway and yaw) should be given as an input in global coordinate system:

$$l_x^i = l_x^{i-1} + V \cdot \Delta_{t_i} \cdot \cos(\Delta\varphi_i \cdot t) \quad (5)$$

$$l_y^i = l_y^{i-1} + V \cdot \Delta_{t_i} \cdot \sin(\Delta\varphi_i \cdot t) \quad (6)$$

$$\varphi^i = \varphi^{i-1} + \Delta\varphi_i \quad (7)$$

Note that $\varphi = 0$ and $\Delta\varphi_i = 0$ when $t \leq T_{straight}$.

The most common way to present these boundary conditions for the used ice FE-model is a table form in ABAQUS. As an example the linear and angular velocities are given the following values: $V = 5$ *m/s* and $\varphi = 1$ ^{o}/s. Suppose now that the first 120 seconds the ship moves straight forward travelling thus 600 m. Then it begins to turn and reaches angle of 90^o in 90 seconds. Three tables are needed: one for each degree of freedom. Straight part of the movement consists of two rows of table: beginning and end of this part. If time – displacement data during rotational movement are written to the table, say, at every 5 seconds, then it takes 18 rows of table to cover 90^o rotation. In this case $\Delta\varphi_i = 5^o$ and $\Delta t_i = 5$ s. It means that, when rotating, the ship moves straight 5 s and then instantly makes a turn of 5^o. In other words, the ship does not move along a smooth rotational curve but along the segmental straight lines (chords) between points on this curve. This simple way to present boundary conditions leads to serious errors in ice force evaluation.

The actual automatic time incrementation of this example needs more than 400000 time increments to complete the analysis successfully. It is impossible to present the boundary conditions (5) to (7) in a table form for each time increment. A special subroutine is developed, where boundary conditions are computed and it is called in by a main program at every time increment making segmental lines (chords) 10000 times shorter for smallest increments.

Ice forces and ship reactions

Four cases of ship movement are considered:

a) - longitudinal velocity $V = 5\ m/s$ and angular velocity $\varphi = 1\ ^o/s$,
b) - longitudinal velocity $V = 5\ m/s$ and angular velocity $\varphi = 0.4\ ^o/s$,
c) - longitudinal velocity $V = 2.5\ m/s$ and angular velocity $\varphi = 1\ ^o/s$,
d) - longitudinal velocity $V = 2.5\ m/s$ and angular velocity $\varphi = 0.4\ ^o/s$.

Total ice forces and, consequently, the ship reactions applied to its centre of gravity are computed in the global coordinate system. When ship turns around the vertical z-axis its local x- and y-axis do not coincide with corresponding global axis's and rotate with angular velocity φ. Rotational moment M_z is the same in both coordinate systems. Then longitudinal and transverse ship reactions should be computed as follows:

$$R_{long} = R_x \cos(\varphi) + R_y \sin(\varphi) \quad (8)$$
$$R_{trans} = -R_x \sin(\varphi) + R_y \cos(\varphi) \quad (9)$$

Longitudinal velocity V = 5 m/s and angular velocity $\phi = 1\ ^o/s$

The whole trajectory of the ship propagation through ice field and imposed displacements on the ship movements (boundary conditions) during the analysis are shown in Figure 4. When failed ice elements drop out of the mesh an empty void occurs between ship hull and the next element edge. To cover this empty space the ship should travel at least a length of the dropped element (about 2 m) which may take quite a number of automatic time increments. Naturally, there are no ice forces and ship reaction within these increments. Time histories of the global reactions R_x and R_y (Figure 5) contain all time increments (about 400000) with all zero reactions. Time increments with zero reactions are removed from local longitudinal and transverse time histories (Figure 6) making these histories much shorter.

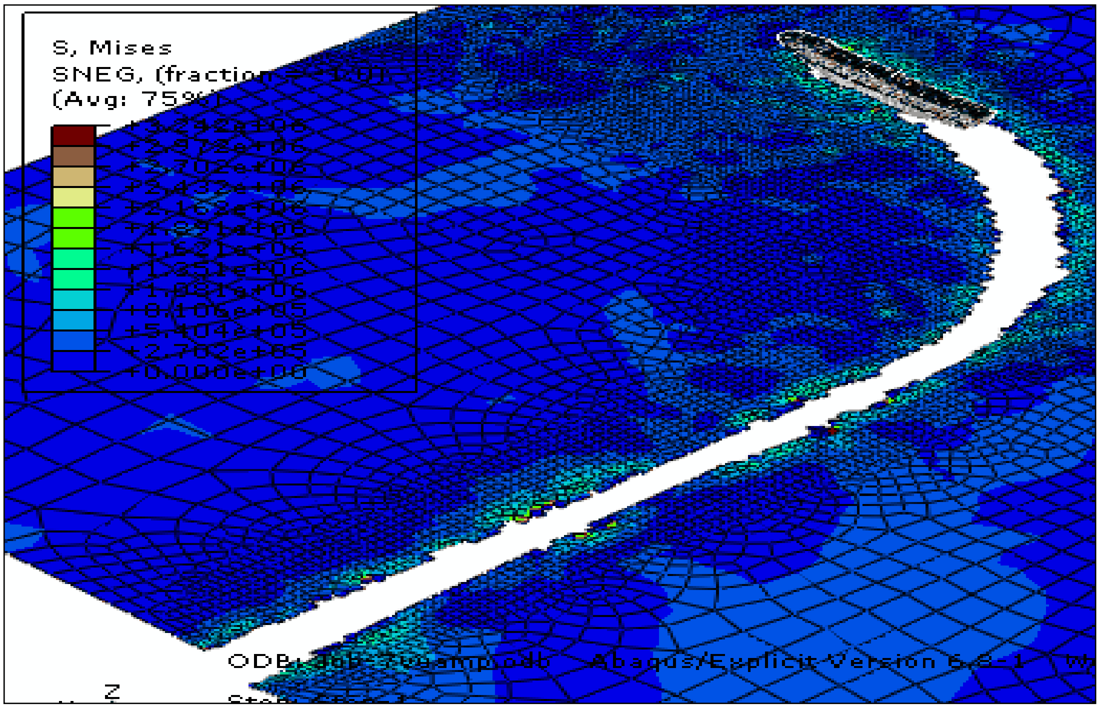


Figure 4a. Ship propagation through ice field. Four node shell elements have been used with the minimum length of 2 m close to the vessel. The extent of the ice field is 1000 m*1800 m. The maximum plotted von Mises stress is 3.2 MPa.

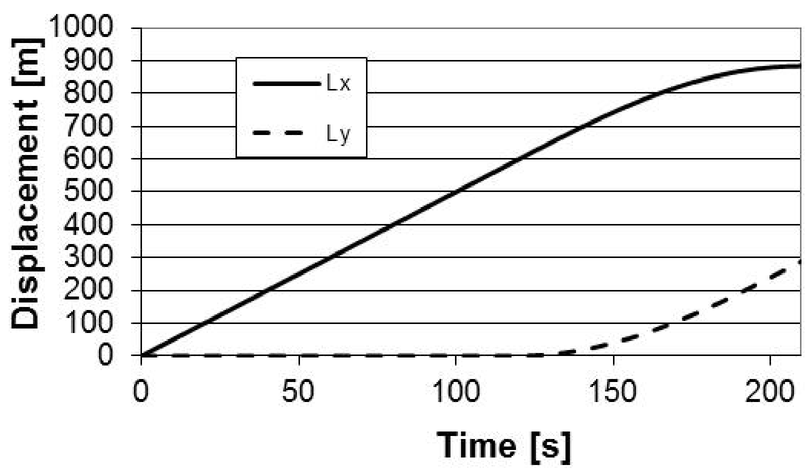


Figure 4b. Global movement imposed onto surge (L_x) and sway (L_y) degrees of freedom when propagating through ice as shown in Figure 4a.

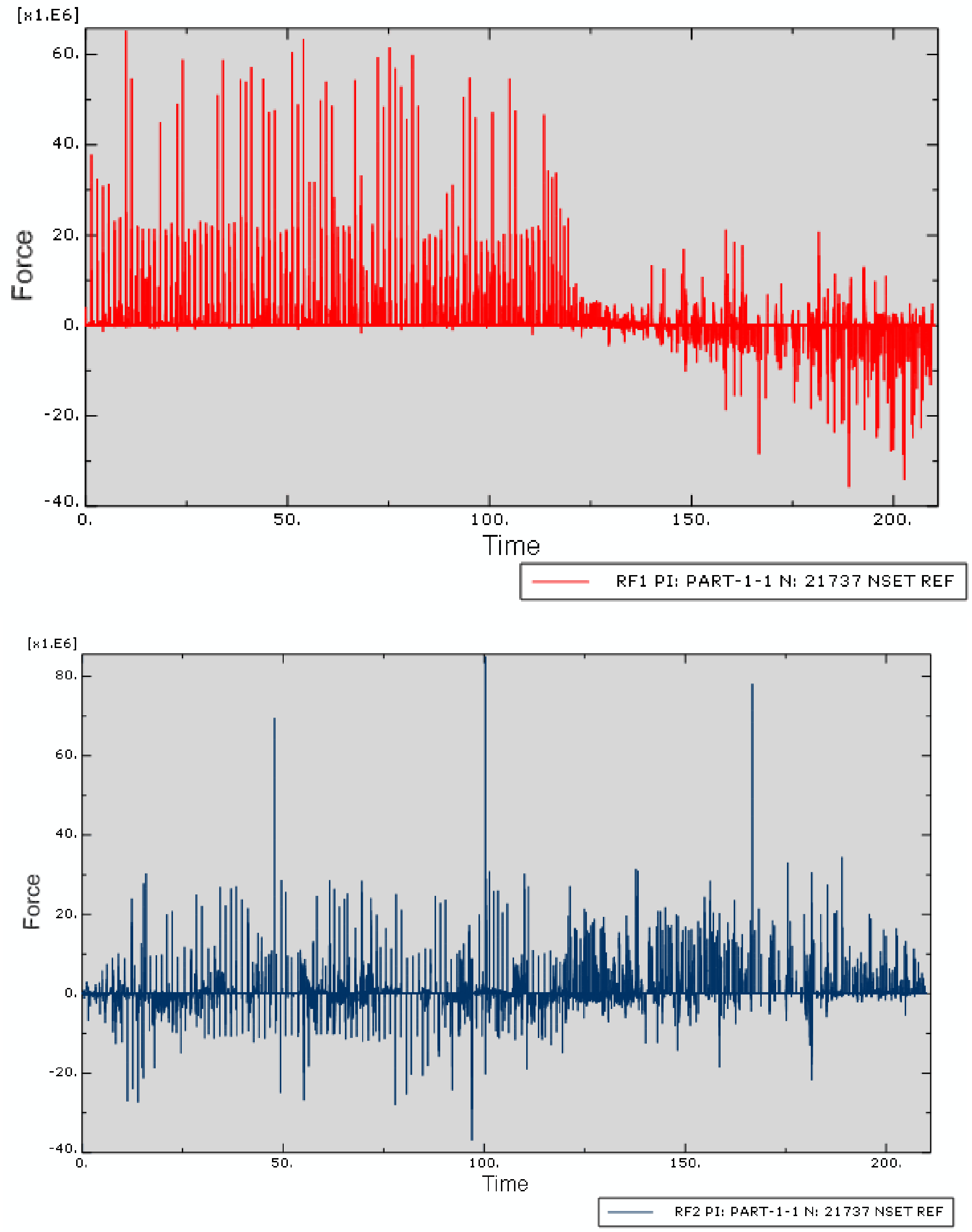
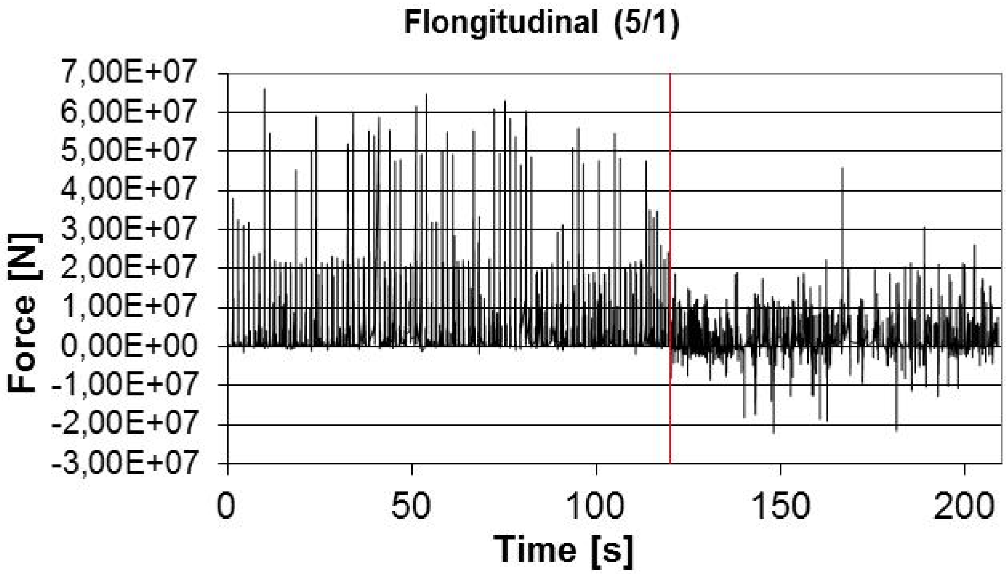


Figure 5. Global reactions and R_x and R_y Force is given in N and time in s.



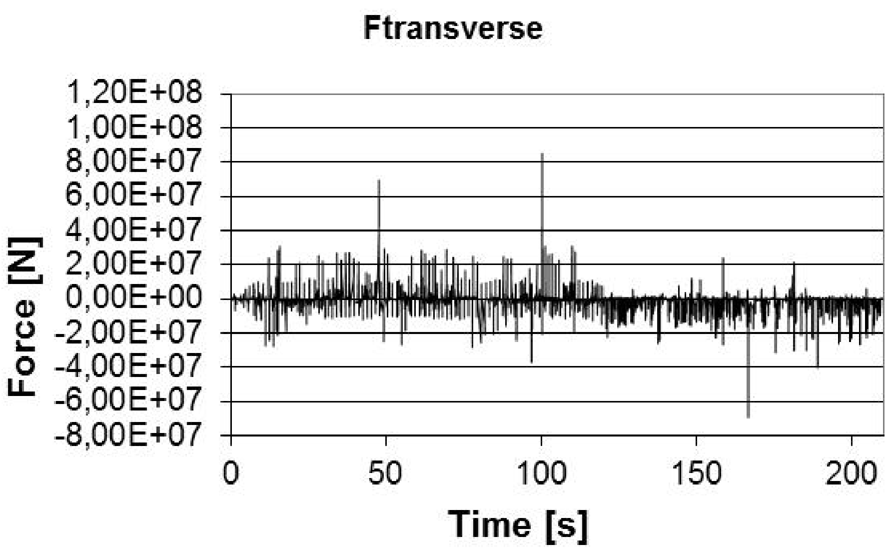


Figure 6. Longitudinal and transverse reactions. Red vertical line indicates when the turning starts.

First 120 seconds the ship moves straight forward traveling 600 m. Next 90 seconds it turns around z-axis making an angle of 90^o and its local x-velocity remains 5 m/s. Global reactions R_x , R_y are shown in Figure 5. Global moment M_z is not shown in this paper.

It is seen from Figure 6 that longitudinal reaction R_x is positive when the ship moves straight whereas ice forces of the same magnitude are negative and oppose the ship movement. When the ship turns within ice field its reaction R_x may be negative. It means that resultant of contact forces of breaking ice around ship hull push the ship forward.

Now the question is whether the ship can overcome the ice field resistance. The ship moves with the constant velocity V developing a kinetic energy $E_{kin} = mV^2/2$, where ship mass is assumed to be the same as DWT to simplify the approach, $m = 23200\ t$ and $V = 5\ m/s$. This amount of energy is the same for each time increment. Consider now an extreme case when undeformed rigid body of the ship runs into undeformed rigid wall. There is no mechanism to absorb kinetic energy of the ship – no distortion of ship structures, or temperature raise or explosion, or bouncing back. Contradiction arises between imposed non-zero constant displacement (surge) at every time increment and zero displacement when ship contacts the wall. The analysis will be stopped with error message. Actually the ice gives up and the ship continues its propagation to some extent no matter what kind of ice it encounters (ice thickness, ice mechanical properties, ice material model etc.). With increasing thickness and hardness of ice, the level of ice forces and, consequently, ship reaction will rise without limits. In order to pass through the next time increment the ship should perform certain amount of work which must not exceed kinetic energy E_{kin} .

Longitudinal velocity V = 2.5 m/s and angular velocity $\phi = 1\ ^o/s$

Now the ship moves 240 s straight travelling the distance of 600 m and then makes a turn of 90^o in next 90 seconds with angular velocity of 1 ^{o}/s. The similar series of pictures as above are presented here.

Global reactions R_x and R_y are shown in Figure 7. Local longitudinal and transverse reactions are shown in Figure 8.

Discussion

Summary of the results

For comparison Figure 9 presents longitudinal reactions for all four cases. When the ship moves straight forward longitudinal reactions are positive and their magnitude is of the same order regardless to the ship velocity. Thus, when ship velocity $V= 5\ m/s$, R_{max} is equal to 65.3 MN (case a) and to 50.1MN (case b). Some difference may be observed in spite that everything for these two cases is the same: ship configuration, ice material model, FE mesh etc. When velocity is $V= 2.5\ m/s$ the difference in reaction magnitude is much greater: R_{max} is equal to 108 MN (case c) and to 52.5 MN (case d).

When ship turns around vertical z-axis, which is the same in global and local coordinate system, longitudinal reaction R_x may be negative as well. It means that the resultant of breaking ice forces acts in positive direction pushing the ship forward. Naturally, according to the solution algorithm, the reaction tries to resist this action pulling the ship backward.

Obviously this is not realistic since ship engine cannot reverse instantly its thrust. Ship continues to move forward with constant velocity. So the hypothetic negative reaction is a consequence of imposed boundary condition (constant velocity of the ship).

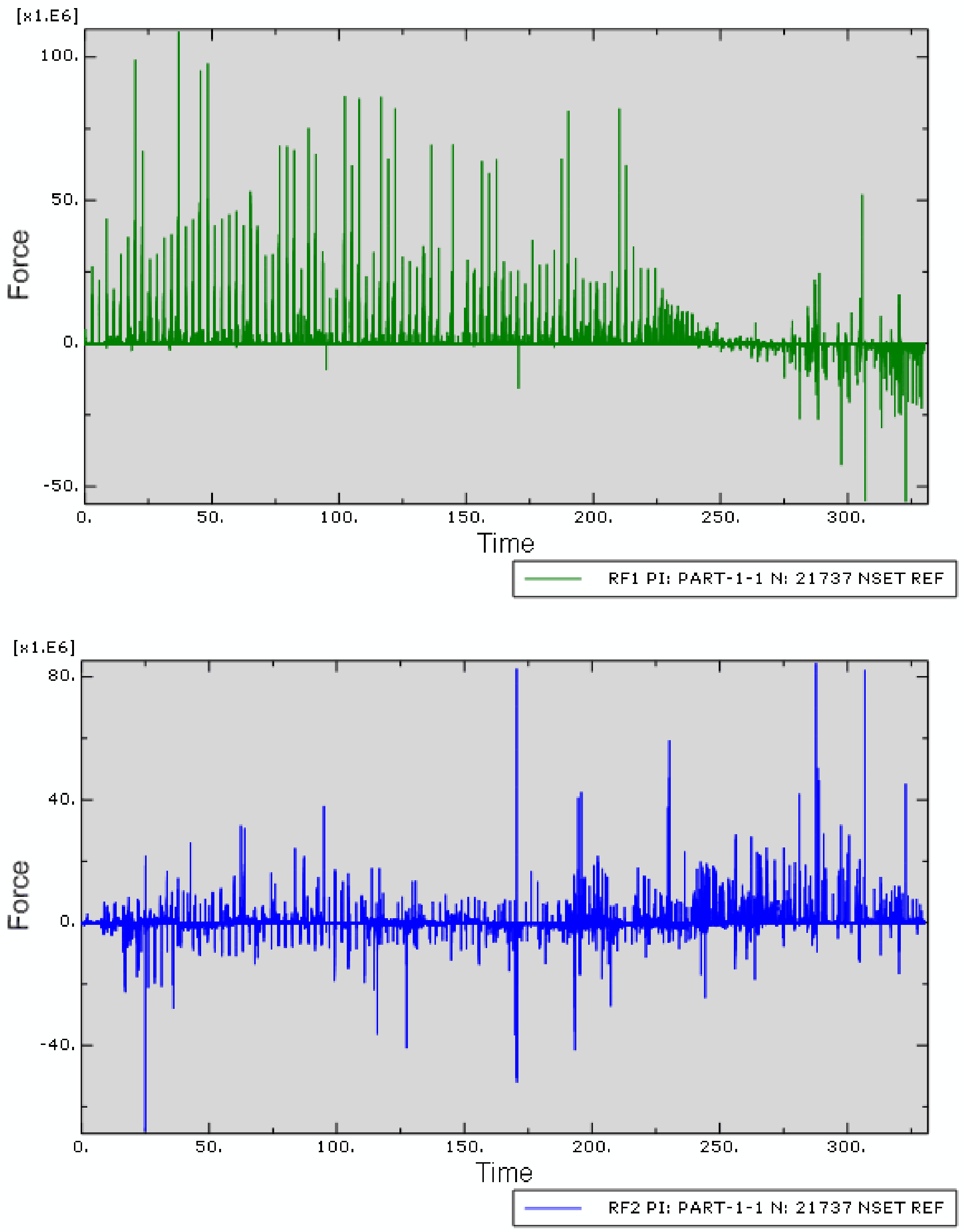


Figure 7. Global reactions R_x and R_y .Force is given in N and time in s.

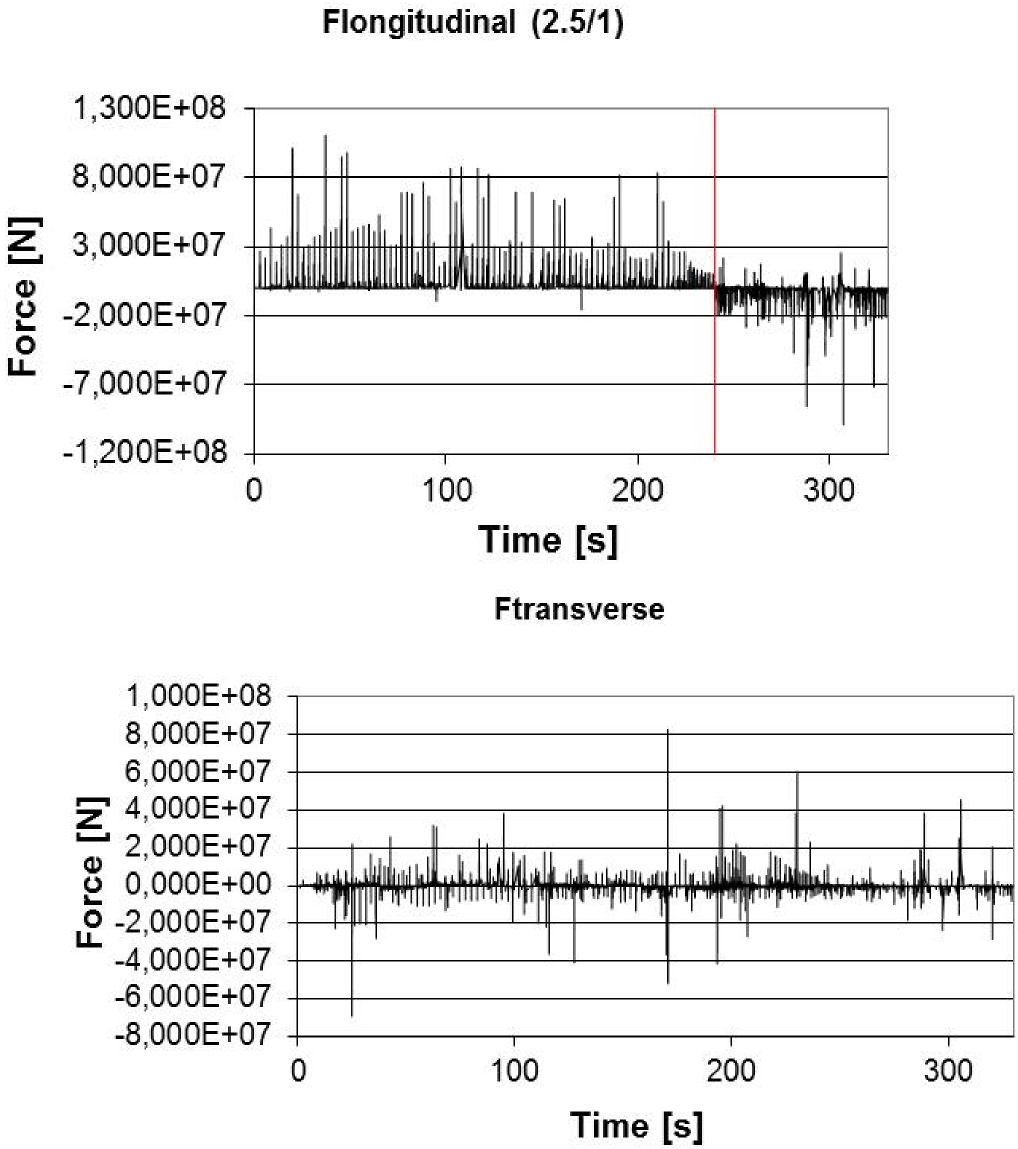


Figure 8. Longitudinal and transversal reactions. Red vertical line indicates when the turning starts.

On the other hand, quite distinct dependence of ice breaking frequency from ship velocity is observed. The frequency of major force peaks when *V= 5m/s* is more than twice as great as when *V= 2.5 m/s.* In case a) the average frequency of major ice force peaks is 0.775 Hz and in case b) it is 0.352 Hz. These numbers correlate with field measurements:

for slender structures the dominant ice breaking frequency is about 8 Hz and for large and stiff (but deformable) it is about 1 Hz [7]. Actually the structure (ship) is completely rigid and the lower level of ice breaking frequency is quite reasonable.

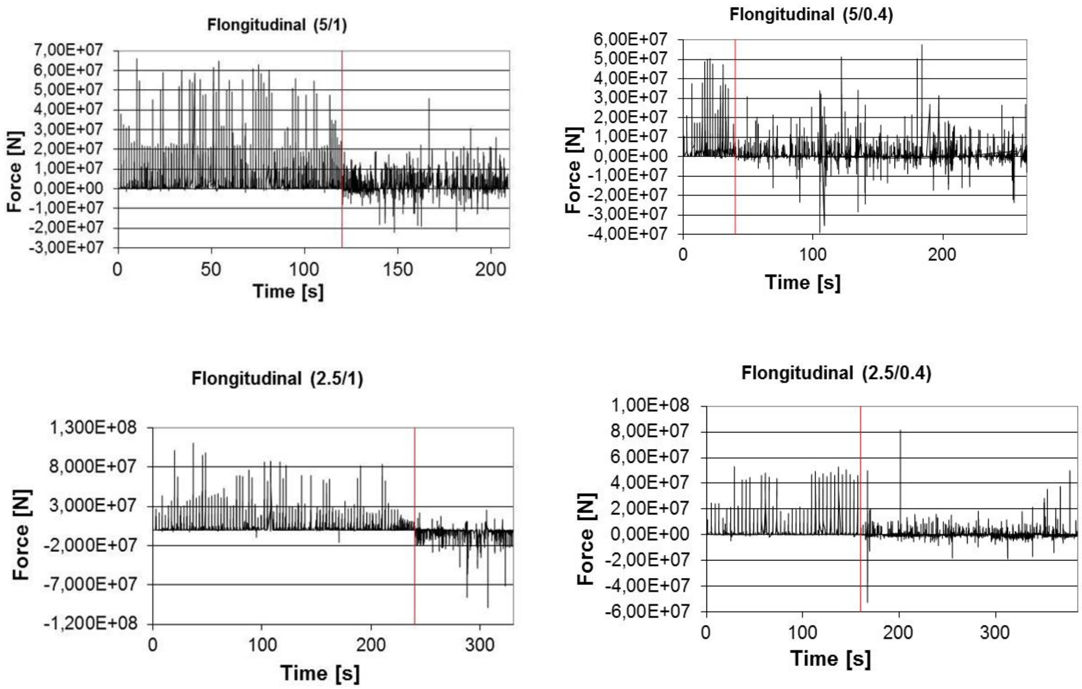


Figure 9. Time histories of longitudinal reactions R_x. Red vertical line indicates when the turning starts.

Comparison with full scale observations

Numerical models should also be validated with some full scale data especially when modelling the ice-breaking and ships navigating ice due the complicated process and sensitivity of the ice mechanical properties to a number of parameters. The available full scale data include e.g. measurements of local ice induced forces along the hull, which after integration along the ship hull forms the total load modelled here. There is available data for ships such as RoRo vessel Arcturus, which is a similar size of vessel as studied here. The local measured forces onboard MS Arcturus have been locally (loaded length 0.35 m) about 0.8 MN/m in short term measurements [8]. This means that e.g. a total load of 80 MN needs a contact length of 100 m and it is possible as the vessel length is 155 m, even though the numerical model seems to somewhat overestimate the load level. One reason being the fact that bending failure of ice is not included in this study, only local crushing is included.

Conclusions

This paper shows an example of FE-modelling to simulate ship navigation and especially the ice-breaking process in ice. The ship-ice interaction is modelled by building a FE-model of ice and using the moving rigid body ship as boundary condition for the FE-model. Then the contact pressure along the ship hull is determined using a modified Drucker-Prager material model for ice and deleting elements when failure criterion for ice is reached. Thereafter the contact forces along the hull are integrated to the centre of gravity of ship hull in the form of resultant forces and moments and ship movements on 3-degree of freedom are updated. It is shown that ice breaking is a random process and time history of reaction forces presents a series of high peaks of very short duration can take place, which have also been observed in full scale.

The main results of this paper can be concluded to be that the improving power of the computers and development of material modelling principles are slowly enabling the numerical modelling of the whole ice-breaking process. Still the modelling of the ship-ice interaction and failure process of ice needs a lot of improvement before these kind of numerical models can be considered reliable for practical design work of ice-going vessels.

Acknowledgement

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