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# ASSESSMENT OF SHIP KINEMATICS AND LIQUID CARGO DYNAMICS DUE TO ICE COLLISION

L. Kniazev [1], V. Tryaskin [2], L. Diebold [1], A. Dudal [1]
[1] Bureau Veritas, Neuilly-sur-Seine, France
[2] State Marine Technical University, Saint-Petersburg, Russia

**ABSTRACT**
The development and transportation of hydrocarbons in Arctic region demands on the cutting-edge vessels enable shipping in severe ice conditions without icebreaking assistance. However independent navigation in ice-infested waters put new challenges for liquid cargo vessels, such as: LNG carriers (LNGC) and oil tankers. Ramming or unexpected collision with multi-year ice and stamukhas can slow down or stop the ship suddenly, resulting in violent sloshing of liquid cargoes, especially LNG.

This study describes an algorithm which first predicts ship kinematics due to glancing impact and ship's jamming in ice to assess the accelerations and velocities for the 6 degrees of freedom (DOF). Second, these accelerations time histories are used in order to perform computational fluid dynamics (CFD) calculations to predict liquid motion inside the LNG tanks and the subsequent sloshing loads. Finally, the obtained sloshing loads are used for the sloshing assessment. Operability of the presented algorithm is demonstrated through some application to a 170000 $m^3$ LNGC sailing in ice.

The algorithm includes solution of theoretical mechanics problem of two bodies' impact, ship and ice motions, ice failure mechanics, LNG motion inside the tanks and sloshing effects of LNG.

## INTRODUCTION

Nowadays, the demand on liquefied natural gas (LNG) and the rise of its global production results in development of new transportation routes all around the world and, particularly, in Arctic region. The biggest energy corporations have announced their plans in exploration of Arctic gas fields. Transit of gas from hydrocarbon field can be done by underground (underwater) pipelines or by sea with the use of LNG carriers. The first solution is costly for long-distance as it requires an installation of compressor stations all along the way of pipeline and is a challenging work for installation and maintenance in severe Arctic environment conditions. Therefore, more often the gas transportation by sea seems to be more cost-effective.

Nowadays the navigation in Arctic region demands on the cutting-edge vessels enable shipping in heavy ice conditions without icebreaking assistance. Ramming or unexpected collision with multi-year ice, ridges or stamukhas can slow down or stop the ship suddenly, resulting in possible violent sloshing of liquid cargoes, especially LNG.

The temperature of LNG during transportation is equal to -162 $^0$C and density is 600 times greater than at gaseous state. The sloshing of LNG could lead to heavy damages of ship's cargo

containment system and results in severe consequences for crew, ship and harsh environmental conditions. Therefore, the consideration of this phenomenon is very important, during the design stage of LNGC's project.
To address this issue, this paper presents a methodology (and an application) enabling from one hand to predict ship kinematics during interaction with ice, and on the other hand to perform sloshing assessment (using CFD calculations).

## PROBLEM DEFINITION

The capacity of LNGC can reach 260000 $m^3$. Today, it exists 3 main types of LNGC, each of them corresponding to a different building technique: membrane, spherical and IHI prismatic LNG ships. As far as membrane technology is more common and is widely applied both on existing and new constructed LNGC (Diebold et al., 2012), only membrane tanks will be considered in this paper.
Design of cargo containment system of LNG carriers requires a special attention to phenomenon of sloshing in tanks. Sloshing is a violent behavior of liquid contents in tanks submitted to the forced vessels' motion on the sea, due to influence of waves in open waters or ship's interaction with ice formations in ice-infested waters.
The present paper describes comparison analysis of sloshing effects, caused by wave actions and ice collision. The analysis is based on consideration of Arctic LNG carrier with membrane tank technology of construction. Capacity of considered vessel is equal to 170000 $m^3$. The ship has a length of 300.0 m. The study is dedicated to calculate sloshing in tanks due to collision with ice field. Assessment of velocities and accelerations of ship, velocities of fluid in tanks and relative pressures (with respect to sloshing pressures encountered during worldwide navigation) on tank membrane is a goal of this paper.

## METHODOLOGY OF ANALYSIS

### *Sloshing - Physical phenomenon*

The sloshing phenomenon in LNG carriers corresponds to LNG motions in the tanks induced by the ship motions during navigation. The sloshing is a multi-scale phenomenon, strongly non-linear and can be violent, i.e., induce damages in the LNG carriers, FLNG or FSRU tanks.
First, the sloshing is a large scale phenomenon. The LNG flow in the tanks depends of the ship motions, tank geometry and filling ratio. Secondly, the sloshing is also a small scale phenomenon. The sloshing impact pressures are deeply influenced by the tank wall local geometry (raised edges of the CCS) and the liquid/gas mixture properties (density ratio, compressibility, surface tension). These local effects have a great incidence on the sloshing impact pressures and explain the large variations in amplitude and space distribution. These large variations and non-regular space distributions of the sloshing impact pressures are observed as well during small scale tests than during tank inspections after incidents (Gervaise et al, 2009). Finally, the sloshing is a complex thermodynamic phenomenon due to the LNG vapor partial condensation during the impact.
In conclusion, the sloshing phenomenon is still too complex to be modeled as a whole making impossible any direct approach. This is the reason why Bureau Veritas (BV) proposes a comparative approach (NI554, 2011). In practice for the 170000$m^3$ LNGC of interest in ice navigation, the comparative approach consists in comparing sloshing loads obtained during ice

navigation (for given scenarios) with the sloshing loads obtained during worldwide navigation for the authorized filling levels (indeed partial filling levels between 10%H and 70%H are not allowed during navigation).

***BV sloshing assessment approach***

There are various technics for appraisal of sloshing effect on ship's CCS (Malenica et al., 2003), (Kim et al., 2011), (Tryaskin et al., 2012). The BV methodology, applied in this paper, is decomposed in three main steps as standard parts of BV comprehensive sloshing analysis during ice navigation:

- Analysis of ship's kinematics in ice & seakeeping analysis in open water: these are key points in each particular sloshing study, with an objective to determine sloshing excitation for CFD calculations and sloshing small-scale model tests.
- CFD calculations: BV requires independent numerical simulations for the review of the model tests (submitted by the designer), for the pump mast strength assessment and for the structural assessment of the inner hull structure behind the CCS.
- Sloshing model tests: sloshing model tests (submitted by the designer) are standard part of BV comprehensive sloshing assessment. These sloshing model tests determine the sloshing loads to be applied on the CCS.

***Analysis of ship's kinematics in ice***

Calculation of ship kinematics was carried out with the use of in-house developed software package of BV, IceSTAR. This tool was developed in co-operation with State Marine Technical University of Saint Petersburg (Russia) and intended for complex estimation of ship performances in ice.

The method of analysis applied in IceSTAR is based on hydrodynamic model of ship and ice interaction (Kurdyumov & Kheisin, 1976). The model is confirmed by long term observations of vessels navigation in Arctic and takes into account wide range of both kinematics parameters of impact and mechanical properties of ice, such as: compression and flexural ice strength, dynamical factor of ice crushing and Young modulus of ice. Ship and ice interaction is considered as inelastic impact of two bodies with certain assumptions:

- Ship is considered as absolutely rigid solid body,
- Propulsive force is equal to zero at the moment of impact,
- Restoring forces and water resistance are negligibly small,
- Impact impulse acts normal to the hull surface in the point of contact,
- Restitution coefficient is equal to zero,
- Ice floe is considered as a fixed object and the ship has relative interaction speed.

The contact area of interaction is described by reference length – $l$ and breadth – $b$. Determination of ship's kinematics builds on the problem of ship side indentation into ice by extrusion of crushed ice from the contact zone. The process of ship's side penetration into ice is depicted in Figure 1, where $\zeta$ is an indentation depth of side structure into ice, $\beta$ is a ship's frame inclination angle at a point of impact.

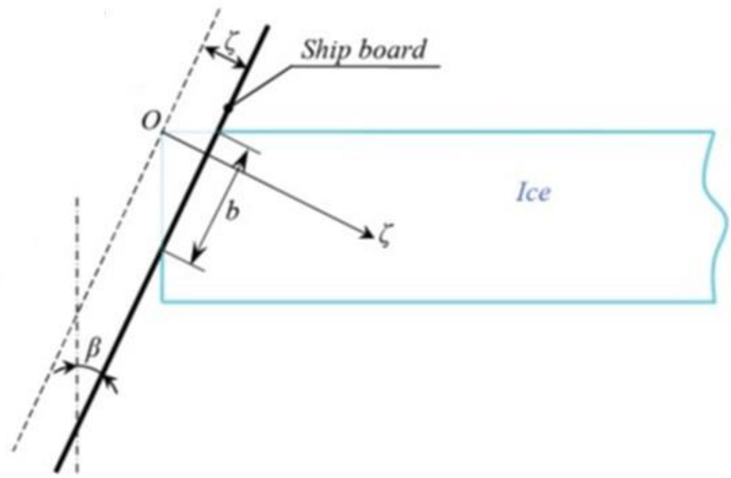



Figure 1. Scheme of ship side impact in ice.

Velocities and acceleration are defined for the time period from the initial contact between ship side and ice edge (*ζ=0*) up to the moment of maximum indentation into the ice. The maximum penetration is defined by following formula (Kurdyumov et al., 1979):

$$\zeta_{\max} = 1.33 \cdot v_0^{7/12} \cdot M_1^{1/3} \cdot a_p^{-2/5} \cdot (2R)^{-1/6} \cdot F_{\zeta} , \qquad (1)$$

where $v_0$ is an initial ship speed in direction of its horizontal axis, $M_1$ is a ship's mass, $a_p$ is a dynamical factor of ice crushing, $R$ is a rounding radius of assumed ice edge and $F_\zeta$ is a dimensionless function of hull shape influence on the value of ship's penetration into ice (*ζ*).
Three types of ship and ice interaction scenarios applied for kinematics calculations may be considered. They are glancing, reflected impact and impact with jamming in ice (Figure 2).

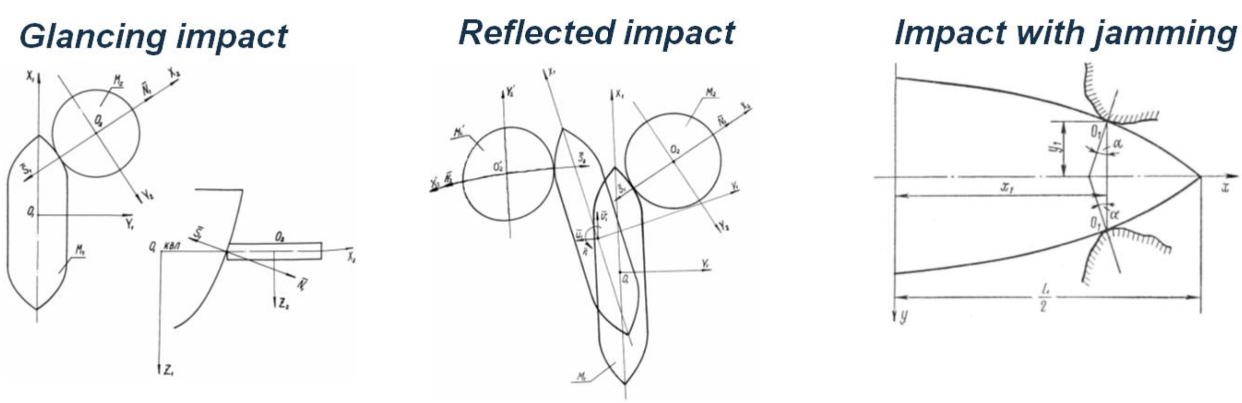



Figure 2. Ship and ice interaction scenarios for assessment of kinematics in IceSTAR.

***Seakeeping analysis of ship in open water***

According to BV Guidance Note (NI554, 2011), for LNGC with worldwide service navigations conditions, environmental data refer to North Atlantic route with significant wave height envelope fitted to 40-year return period.
The hydrodynamic analysis is carried out using HydroSTAR® software, a 3D diffraction/radiation code developed for wave-body interactions, including various features such as multi-body interaction, effects of forward speed and internal liquid motions. The Response

Amplitude Operators (RAO) are first calculated. These calculations take into account the coupling between seakeeping and liquid motions inside the tanks (HydroSTAR®).
Based on these RAO and taking into account the worldwide service conditions for the 170000 $m^3$ LNGC of interest, seakeeping calculations are carried out in order to derive the irregular motions to be applied to the tank for the CFD calculations.

***CFD calculations***

CFD calculations are carried out using OpenFOAM. The solver used for this study is interDyMFoam from OpenFOAM. The interDyMFoam is a solver for two incompressible, isothermal immiscible fluids using a VOF (volume of fluid) phase-fraction based interface capturing approach, in a moving mesh domain. This solver solves the well-known Navier-Stokes equations, recombined for a moving mesh. Following are presented the equation in the punctual versions and written for a moving control volume:

$$\begin{cases} \nabla \cdot U = 0 \\ \dfrac{\partial \rho U}{\partial t} + \rho U \cdot \nabla U = \nabla p + \mu \Delta U + f \end{cases} \tag{2}$$

$$\begin{cases} \int \nabla \cdot U \, dV = \int \nabla \cdot U_G \, dV \\ \int \left( \dfrac{\partial \rho U}{\partial t} + \rho U \cdot \nabla U \right) dV = \int \left( \nabla p + \mu \Delta U + f \right) dV + \int \left( \rho U \cdot \nabla U_G \right) dV \end{cases} \tag{3}$$

The term UG represents the velocity of the mesh. Basically a new virtual flux is added to the equation to take into account the moving of the mesh. The time marching is performed with an Eulerian implicit approach, that increases the stability of the solution. This solver uses a volume of fluid (VOF) method to track the interface between the two fluids, so it solves the classical VOF equation, where alpha represents the fraction of fluid present in each cell, and all the physical quantities representative of the fluids characteristics are weighted by this fraction:

$$\frac{\partial \alpha}{\partial t} + \alpha \cdot \nabla U = 0$$

$$\begin{cases} \rho = \alpha \rho_1 + (1 - \alpha) \rho_2 \\ \mu = \alpha \mu_1 + (1 - \alpha) \mu_2 \end{cases} \tag{4}$$

In this version of OpenFOAM, a new semi-implicit variant of MULES is introduced which combines operator splitting with application of the MULES limiter to an explicit correction rather than to the complete flux (www.openfoam.com).

***Sloshing model tests***

Despite the fact that sloshing model tests are considered as an essential part of LNGC design process, the goal of the present paper is to describe analytical methods for assessment of sloshing loads during ice navigation. Therefore the full sloshing model tests were not carried out for considered case study. However, several sloshing tests were performed for validation of CFD methods, applied in this paper.

***CFD validations of sloshing assessment***

A validation of sloshing assessment approach is here presented through some comparison with BV dedicated sloshing model test which consists in irregular simulation for a 5 hour duration at full scale (Froude scaling is used for excitation) (Diebold et al., 2013). This 5-hour simulation (only sway motion in this section) of the test case study is run using OpenFOAM. Four different structured hexahedral meshes are used. The total number of cells used to define these four meshes is equal to 60,000; 120,000; 180,000 and 240,000 cells. The last mesh with 240,000 cells (cell average size is 0.55 m at full scale) is illustrated hereafter.

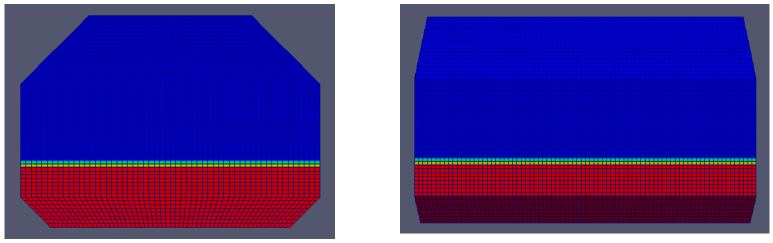


Figure 3. OpenFOAM structured hexahedral mesh.

The loss of fluid during whole simulations is equal to zero, that confirms the accuracy of CFD calculations. Liquid global forces calculated by OpenFOAM for the 4 numerical meshes are compared to these ones extracted from the model tests measurements at the end of the simulation (Figure 4).

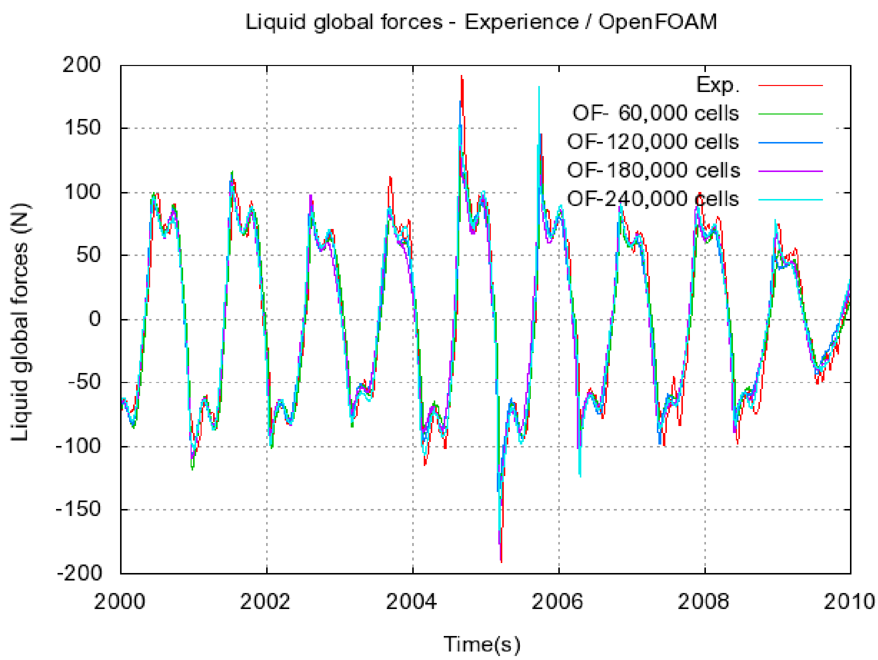



Figure 4. Liquid global forces comparison between experience and OpenFOAM CFD calculations for 4 different meshes.

Figure 4 shows, that agreement between the measured and calculated liquid global forces is excellent till the end of the 5-hour simulation (2150 seconds at model scale). Moreover, all meshes seem to be in good agreement with the experiments.

Another way to figure out the comparison between the measured and calculated liquid global forces is to plot the exceedance rate function. The comparison between measured and calculated liquid global forces (for the 3 different meshes 60000, 120000 and 240,000 cells) exceedance rate function is presented in Figure 5. Green points on a diagram corresponds to CFD simulation with

240,000 cells mesh, blue points to 120,000 cells mesh and purple points to 60,000 cells mesh. Red points on the diagram correspond to sloshing model test. The Weibull fittings for the experiments and CFD calculations are plotted with corresponding colored lines.

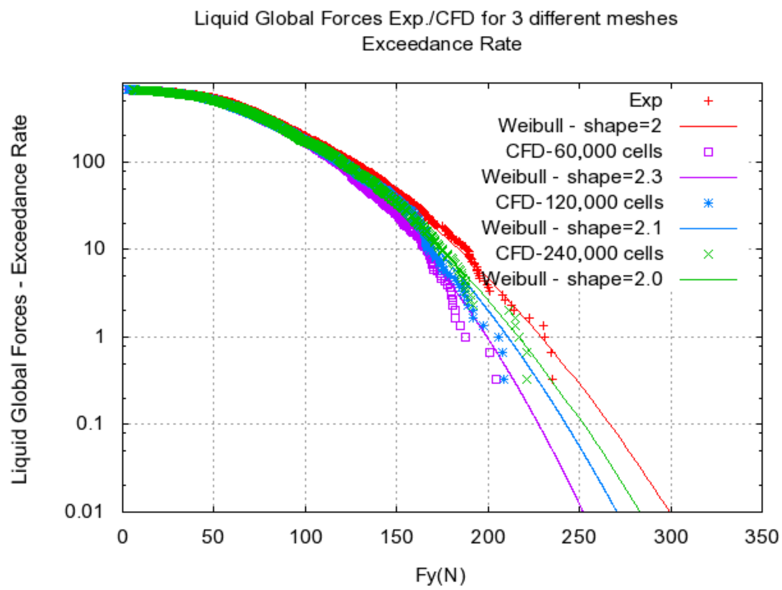



Figure 5. Exceedance rate (per hour) functions for the measured and calculated liquid global forces.

Figure 5 demonstrates good agreement between measured and calculated global forces exceedance rate functions. Moreover, finer model mesh leads to better agreement between CFD simulations and experiments. It proves that the global flow inside the tank is well predicted by CFD calculations. Thus, the described sloshing assessment approach can be used for modelling of liquid velocities and motions in CCS.

***CFD Post-processing tools***

One of the major drawbacks of the sloshing model tests is the impossibility either to cover all the tanks' boundaries with pressure sensors. Indeed, the state of the art sloshing model tests relies on pressure sensors clusters which can be located only at certain locations on the tanks' walls. Thus, it is impossible to get a complete view of the sloshing impact pressures over the tanks' boundaries.

In principle, CFD simulations should able to get a complete view of the impacts over the tanks' boundaries by recording all the data for all the time steps of the simulations. However, classical CFD studies usually considers also (like sloshing model tests) only predefined hot spot zones since storage of all the data for all the time steps requires too much space on disks.

In order to circumvent this issue, a dedicated in-house processing tool called "Dynamic Probe" is used. At each time step, the fluid flow is analyzed; sloshing impacts are detected with respect to a pressure or normal velocity criteria. On the fly sensors are created accordingly leading to an exhaustive check of the impacts. So this dedicated BV tool provides a complete knowledge of all the sloshing events over the tank's boundaries during the complete simulation.

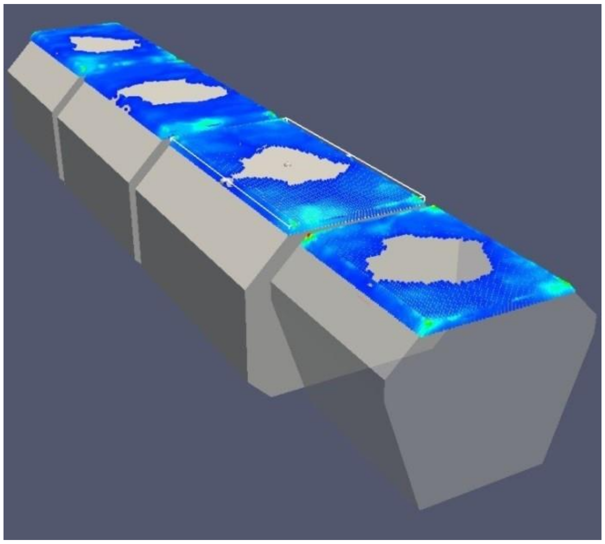


Figure 6. Example of post-processing for the pressure using the dedicated processing tool called “Dynamic Probe” (detection zone was deliberately constrained to the ceiling zone).

Using this processing tool ensures that all sloshing impacts are detected wherever and whenever these impacts occur on the tanks walls.

## MODELLING & RESULTS

According to described methodology, sloshing loads were calculated for considered LNG carrier of 170000 $m^3$ for the case of heavy ice ramming. The results of this modelling are presented using comparative approach. Sloshing loads, obtained from considered scenario of ship and ice interaction are compared to these ones obtained from the analysis of ship navigation in open water according to worldwide navigation condition requirements, given in (NI554, 2011).

### *Design scenario*

Calculations of ship kinematics in ice were performed for scenarios of glancing impact, reflected impact and impact with jamming in ice. Ice properties and ship speed were taken identically for all scenarios. Analysis showed that the most dangerous interaction case corresponded to impact with jamming, as far as it leaded to bigger ship accelerations during ice contact. Therefore, the scenario of the impact with jamming was chosen for the goals of the present paper.
Sloshing calculations were performed for the case of ship navigation via Northern Sea Route, in the Kara Sea and the Barents Sea during winter-spring season. The ice thickness is assumed to be 2.1 m, according to the monitoring data from the Barents Sea, summarized in (Løset et al., 1997), flexural ice strength is taken to be equal to 0.5 MPa, corresponding to (Gavrilo et al., 1995). The design scenario presumes that ship’s hull hits a heavy ice ridge by two sides symmetrically. The ship is supposed to work ahead in ramming mode with a speed of 8 knots and to stop in the end of penetration, as shown in Figure 7. The ship's speed corresponds to a permissible limiting speed in ice for the vessel of interest.

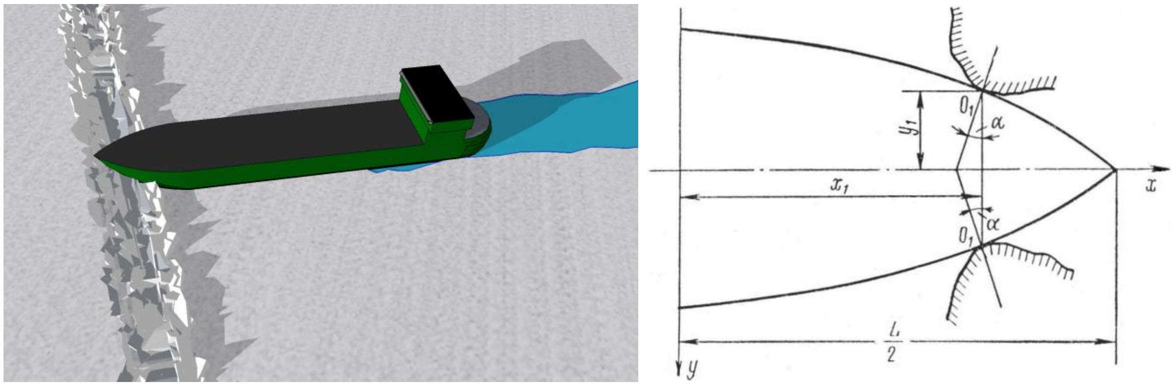


Figure 7. Illustration of scenario of impact with jamming.

According to Eq.1 the hull inclination angles affect the value of maximum penetration depth as well as the values of ship velocities and accelerations. Therefore, analysis of ship's kinematics was carried out for several contact points along bow and bow intermediate regions to define the most dangerous impact point corresponding to the highest accelerations. Results of ship's kinematics calculations are shown in Figure 8. Accelerations, velocities and ship indentation in ice in longitudinal direction are plotted in time by green, red and blue line correspondingly.

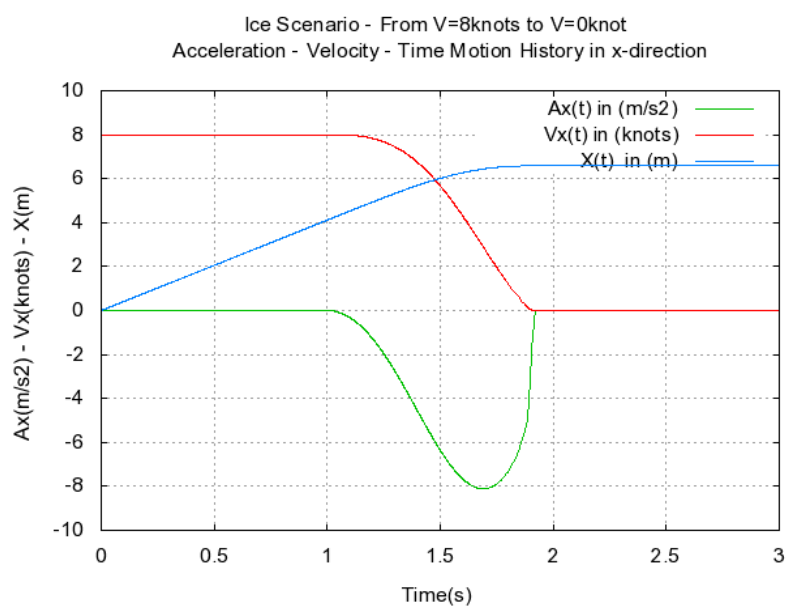


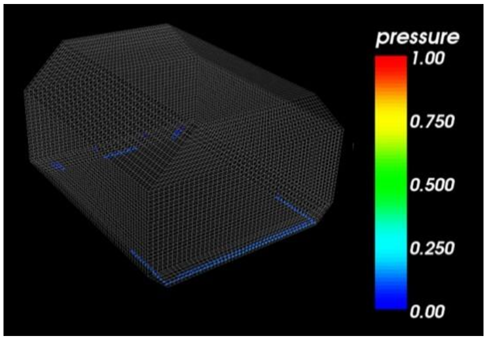

Figure 8. Time history of ship's accelerations and velocities due to ice ramming of ship at the speed of 8 knots.

***Sloshing loads - Comparison of design scenario with worldwide navigation requirements***

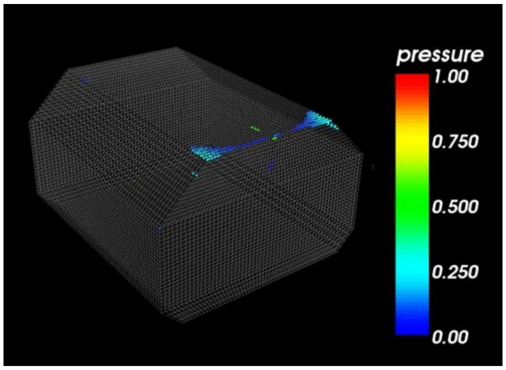
For the proposed design ice scenario (Figure 7), 5 filling levels were tested:

- 10%H corresponding to the upper limit of the low filling levels accepted in navigation;
- 70%H corresponding to the lower limit of the upper filling levels accepted in navigation;
- 80%H for the discretization between 70%H and 95%H;
- 90%H for the discretization between 70%H and 95%H;
- 95%H corresponding to the standard operational filling level.

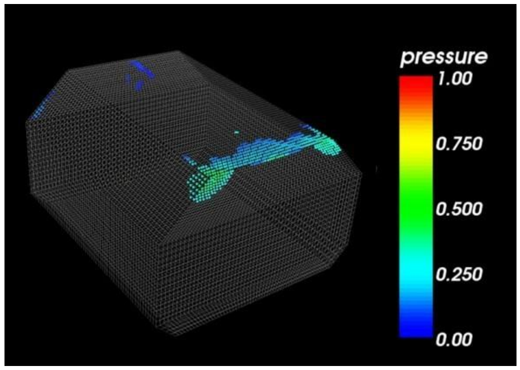
For the CFD post-processing, one has considered the maximal quasi-static pressures calculated by the CFD calculations. Keeping in mind the comparative approach that was introduced before, we compare the sloshing loads obtained during the ice collision (quasi-static pressures) with the sloshing loads (quasi-static pressures) obtained during worldwide navigation. The sloshing loads obtained during worldwide navigation were subject of dedicated BV analyses. Main results in terms of quasi-static pressures can be found in BV rules. Finally, the ratio of sloshing loads obtained during ice collision and sloshing loads during worldwide navigation are given hereunder (Figure 9).



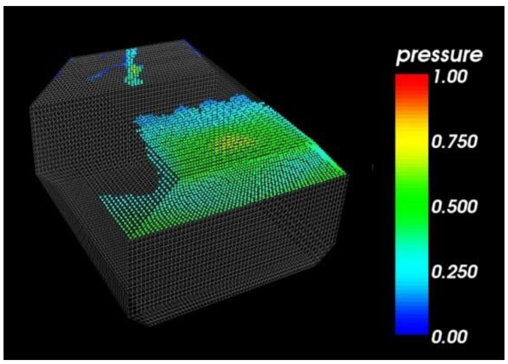

a. 10% of tank filling



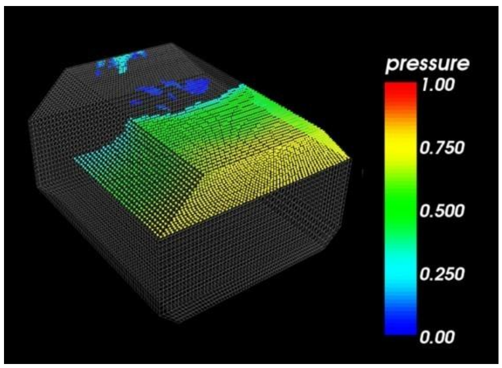

b. 70% of tank filling




c. 80% of tank filling




d. 90% of tank filling




e. 95% of tank filling

Figure 9. Relative quasi-static pressures (ice ramming/worldwide navigation) for different cases of tank loading.

All the sloshing loads ratios (quasi-static pressures) between ice collision and worldwide navigation are below 1.0. The maximum ratio is obtained for the very high filling levels R=90%H and R=95%H, the ratio is then equal to 0.75. It means that sloshing loads calculated for the proposed ice collision scenario are below the sloshing loads expected during worldwide navigation. In other words, the vessel of interest (LNG carrier of 170000 $m^3$) is capable to sustain the sloshing loads occurring during the ice collision scenario considered here.

**CONCLUSION**

This paper presents the methodology applied in BV for assessment of sloshing loads due to ship collision with ice. The methodology includes analysis of ship's kinematics in ice and CFD calculations of fluid motions in tanks of LNG carrier. In order to validate the described approach, sloshing analysis was carried out for ice navigation of the 170000 $m^3$ LNG carrier. Design scenario considers ship ramming of heavy level ice in the Kara and Barents Seas at a speed of 8 knots. Sloshing loads obtained from calculation of design scenario are analyzed using comparative approach. Comparative analysis showed that for considered design ice scenario sloshing loads are less than loads expected during open water navigation, considering worldwide navigation service requirements (NI554, 2011). The filling level inside the tank has an influence on the ratio of sloshing loads in ice to loads in worldwide navigation. But the value of this ratio is less than 1. The maximum ratio is equal to 0.75, when the filling levels are equal to 90%H and 95%H. Thus, we can conclude that the LNG carrier of interest is capable to sustain the sloshing loads occurring during the ice collision scenario considered in this paper.

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