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SIBIS: A NUMERICAL ENVIRONMENT FOR SIMULATING OFFSHORE OPERATIONS IN DISCONTINUOUS ICE

Ivan Metrikin[1], Arne Gürtner[1]
Basile Bonnemaire[2], Xiang Tan[2], Arnt Fredriksen[2], Dmitry Sapelnikov[2]
[1] Arctic Technology Department, Statoil ASA, Trondheim, Norway
[2] Multiconsult AS, Tromsø, Norway

ABSTRACT

Exploration and production of oil and gas resources in harsh offshore environments may require operating in contact with ice. Therefore, there is a need to understand the operational implications of ice actions on stationkeeping of floating platforms, offloading of hydrocarbons, evacuation and rescue of personnel and oil spill response operations. This knowledge is especially important in the early phase of field developments projects, because ice actions can strongly affect the costs of the hull structure of a floating platform, as well as the design of its mooring and propulsion systems. Furthermore, estimating the operational expenditures of potential support operations requires the knowledge of ice loads on vessels in transit during physical ice management and other special operations such as iceberg towing through broken ice. This paper presents a novel numerical environment for simulating such complex and critical offshore operations with high fidelity and performance: SIBIS, which stands for "**S**imulation of **I**nteraction between **B**roken **I**ce and **S**tructures". The numerical model estimates both local and global ice actions on vessels and offshore structures, and the corresponding structural response in time domain. This paper describes the overall structure and capabilities of the SIBIS package, and presents some examples of its successful usage in industrial projects.

INTRODUCTION

Oil and gas industry operations in deep-water Arctic areas are currently taking place primarily during the open water season. For example, floating drilling and production platforms are routinely operating in the Barents Sea and offshore Newfoundland and Labrador. However, certain offshore sites may experience rare sea ice intrusions, and in such situations the performance of a drilling or production facility shall remain safe and robust. It is known that in all practical sea ice intrusion situations the ice cover approaching the operational site of a floating platform will be discontinuous, i.e. broken into discrete ice features of various shapes and sizes either by waves or by the operator's ice management fleet.

The capability of a platform or a vessel to operate in a broken ice field depends on the level of ice actions. These actions, in turn, depend on the ice-structure interaction processes which involve complex contact mechanics: ice material failure, rigid-body motions of the broken ice pieces, ice-ice and ice-structure friction, ice clearing processes and fluid effects. Moreover, the boundary conditions of the broken ice domain may have a strong influence on the load-response relationship of the dynamical ice-structure system, leading to a range of highly nonlinear and complex physical behaviours. Such interactions are very challenging to describe and predict, and the industry lacks reliable engineering tools for computing the response of structures to actions from broken ice.

Modelling and simulation of the global loads on structures from broken ice is especially challenging because of the apparent discrete-continuum nature of the broken ice material. On the one hand, it is composed of distinct ice floes that can be described as separate independent bodies, i.e., a discrete system. On the other hand, during ice drift and ice-vessel interactions the ice floes can crush, split, buckle and fracture, producing new floes and brash ice. Such material behaviour can be difficult to describe from a purely discrete perspective, and calculations of stresses and strains inside the individual ice floes may be necessary. Nevertheless, several empirical and numerical methods have been developed for estimating global loads on offshore structures from broken ice.

State-of-the-art empirical methods can be listed as follows:

- Methods based on regression analyses of model tests performed in pack ice conditions (Spencer and Molyneux, 2009; Woolgar and Colbourne, 2010; Wang et al., 2010);
- The "equivalent level ice thickness" method of Keinonen et al. (1998);
- Formulae derived from full-scale measurements of the global ice loads on the Kulluk platform (Wright, 1999; Croasdale et al., 2009; Palmer and Croasdale, 2013).

However, those empirical formulations produce only one estimate of the ice load for a certain combination of ice-vessel parameters. For practical applications that can be insufficient, especially when reliable information about the dynamical and statistical characteristics of the ice load signal are needed for an engineering application (such as the mean and peak values). Although this limitation can be circumvented by either a statistical method (Metrikin et al., 2013) or a "max-to-mean ratio" method (Eik and Aksnes, 2010; Eik, 2011), such methods do not seem to be widely applied in the industry. Another promising empirical approach is based on direct usage of experimental data of the measured global ice loads, which are used as input to a numerical model of an offshore structure. Although this method has been widely used in dynamic positioning (DP) applications (Jenssen et al., 2009; Hals and Jenssen, 2012; Metrikin et al., 2013), the most challenging stationkeeping scenarios, such as DP position loss due to insufficient thrust, cannot be reliably replicated by this method as demonstrated by Jenssen et al. (2012) and Metrikin et al. (2013).

It is generally accepted that a more promising approach is to utilize a high-fidelity numerical model, based on the fundamental laws of physics, to estimate the ice loads. Different numerical techniques have been historically applied for this purpose:

- The Finite Element Method (FEM) implemented in a commercial software package such as LS-DYNA, ANSYS or ABAQUS (Wang and Derradji-Aouat, 2010; Wang and Derradji-Aouat, 2011; Millan and Wang, 2011; Lobanov, 2011; Kim et al., 2013; Lee et al., 2013; Kim et al., 2014);
- Implementation of the Particle-In-Cell (PIC) method introduced by Sayed (1997) and further developed at the National Research Council of Canada (Barker et al., 2000, 2002, 2014; Barker and Sayed, 2012; Iyerusalimskiy et al., 2012; Sayed and Barker, 2011; Sayed and Kubat, 2011; Sayed et al., 2012a, 2012b, 2014a, 2014b, 2015; Vachon et al., 2012);
- Various implementations and further developments of the classical penalty-based discrete element method of Cundall (1971). Modern implementations include:
    - Finite-Discrete Element Method (FEM-DEM) numerical code developed in-house by the Department of Applied Mechanics at Aalto University in Finland (Tuhkuri, 2005; Paavilainen et al., 2006, 2009, 2011; Paavilainen and Tuhkuri, 2012; 2013; Paavilainen, 2013; Polojärvi and Tuhkuri, 2009, 2010, 2013,

2014; Polojärvi et al., 2012, 2015; Polojärvi, 2013; Haase et al., 2010; Ranta et al., 2014);
    - Model of the Krylov State Research Centre in Saint-Petersburg, Russia (Karulin and Karulina, 2010, 2011, 2013, 2014);
    - The DECICE code owned by the Oceanic Consulting Corporation in Canada (O'Brien, 2004; Quinton, 2006; Lau, 2006; Lau and Ré, 2006; Lawrence, 2009; Liu et al., 2010; Zhan et al., 2010; Park et al., 2011; Lau et al., 2011; Molyneux et al., 2012a, 2012b; Zhan and Molyneux, 2012);
    - And other independent developments (Selvadurai, 2009; Sun and Shen, 2012; Vroegrijk, 2012; Ji et al., 2014, 2013).
- Recently, a new method for calculating broken ice loads on structures was proposed - the GPU-based event mechanics (GEM) (Daley et al., 2012, 2014a, 2014b; Alawneh et al., 2015). The background theory and governing equations of that method can be found in Alawneh (2014), and validation was performed against small-scale experiments where the vessel and the ice floes were modelled by polypropylene blocks (Alawneh, 2014; Alawneh et al., 2015).

In the authors' opinion, one of the most promising numerical approaches for simulating ice-structure interaction is the nonsmooth discrete element method. For ice mechanics applications that method was pioneered by Konno and Mizuki (2006a), and was developed further in their subsequent publications (Konno and Mizuki, 2006b; Konno et al., 2007, 2011, 2013; Konno and Yoshimoto, 2008; Konno, 2009a, 2009b; Konno and Saitoh, 2010; Watanabe and Konno, 2011; Ishibashi et al., 2014). A similar approach is utilized in the numerical model developed by the Ship Modelling and Simulation Centre (SMSC) in Trondheim, Norway (Amdahl et al., 2014; Gürtner et al., 2012; Lubbad and Løset, 2011), and in the simulator product developed by the Norwegian University of Science and Technology (Metrikin et al., 2012a, 2012b, 2013, 2015; Metrikin and Løset, 2013; Kerkeni et al., 2013a, 2013b; Kerkeni and Metrikin, 2013; Scibilia et al., 2014; Østhus, 2014; Metrikin, 2014; Kjerstad and Skjetne, 2014; Kjerstad et al., 2015). Furthermore, the nonsmooth discrete element approach is presumably utilized in the new ice simulation tool using a multi-model program developed by Cervval, Bureau Veritas and Technip (Septseault et al., 2014, 2015). Finally, another numerical model, seemingly based on similar theoretical principles, is currently being developed independently by the Norwegian University of Science and Technology within the framework of the Sustainable Arctic Marine and Coastal Technology (SAMCoT) centre for research-based innovation (Lubbad and Løset, 2015).

This paper presents a novel and independently developed numerical approach for estimating the response of vessels and offshore structures to broken ice actions. The approach is based on the nonsmooth 3D formulation of the discrete element method, and it is implemented in a software package which offers a complete engineering environment for simulating various offshore operations in contact with ice. The forthcoming sections of the paper describe the structure and capabilities of the new software package, as well as some of its validation cases and successful usage examples from real industrial projects.

SIBIS MODEL DESCRIPTION

SIBIS (**S**imulation of **I**nteraction between **B**roken **I**ce and **S**tructures) is a novel simulation tool which has been developed jointly by Statoil and Multiconsult as a complete numerical environment for efficient simulations of offshore structures in discontinuous ice conditions in time domain. The main application of the SIBIS numerical model is simulating the response of floating structures to global pack ice loads, but the software can also be used for simulating ice actions on fixed offshore and coastal structures in intact or deformed (e.g. ridged) ice, as well as for a wide spectrum of other ice engineering challenges, such as for example under-hull ice material transport investigations. On the highest level the SIBIS numerical tool is structured as shown in Figure 1.

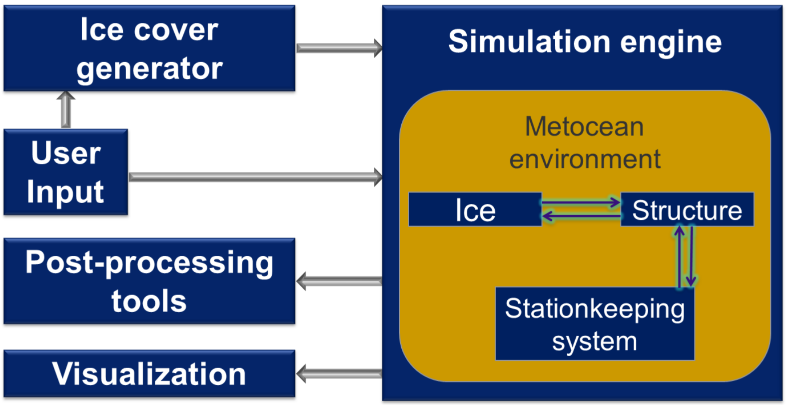

Figure 1. Top-level structure of the SIBIS simulator product.

User's input to the numerical model includes the 3D surface mesh of the simulated structure, its mass and inertia tensor, as well as the stationkeeping system configuration. The structure can be moored or thruster-assisted (on DP), as well as fixed to a planar motion mechanism (PMM) or to a towing carriage in a virtual ice basin. Other user-defined input parameters to SIBIS include the densities of the surrounding water and air, current and wind velocities and the acceleration of gravity. The simulated physical domain can be restricted by static boundaries, if the objective of the user is to simulate an operation close to a coastline, or a model-scale experiment in a restricted ice tank.

Both full-scale and model-scale ice covers can be modelled in SIBIS. An example of a model-scale ice field is shown in Figure 2, and the corresponding floe size distribution is shown in Figure 3. An example of a full-scale broken ice field is presented later in this paper.

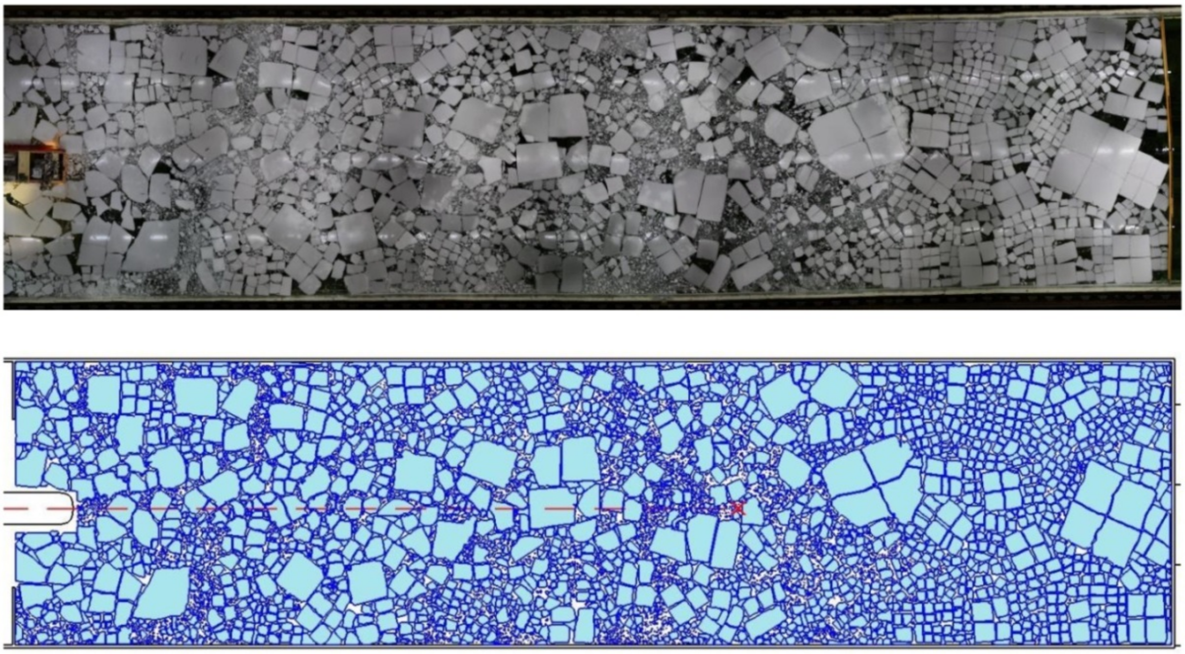

Figure 2. Top: broken ice field picture from the large ice tank of the Hamburg Ship Model Basin (HSVA), bottom: the corresponding ice field input to SIBIS.

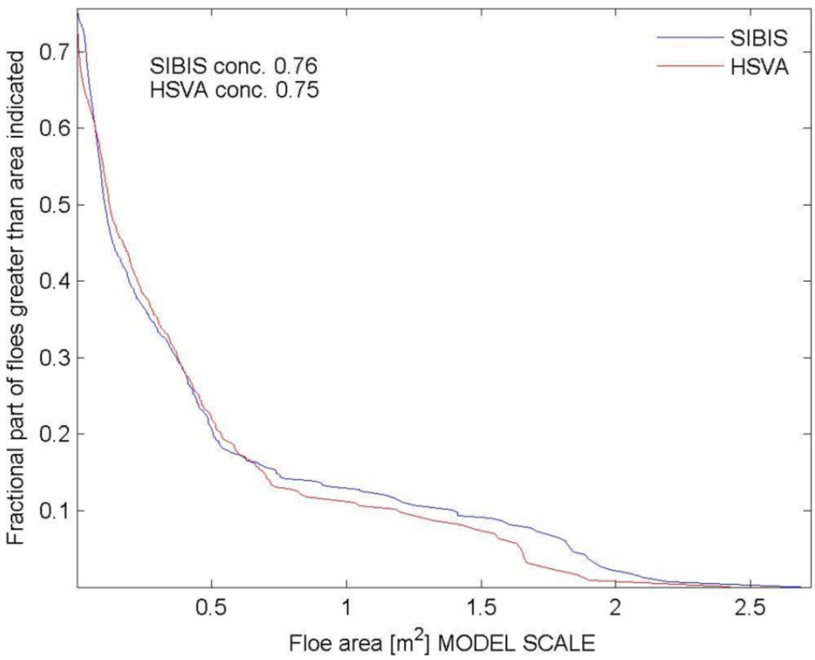

Figure 3. Comparison of floe size distributions from the two images in Figure 2.

The simulated ice cover in SIBIS is composed of individual ice fragments that respond in 6 degrees of freedom (DOF) to accurate fully-nonlinear hydrostatic forces, skin and form drag forces, damping loads and contact forces from other ice floes, structures or boundaries in the simulation domain. Each ice fragment is characterized by a set of individual physical properties (geometry, density, flexural and compressive strengths, Young's modulus, Poisson's ratio and friction coefficients). Therefore, it is possible to simulate ridge fragments and rubble fields in the ice cover, as well as multiyear or glacial ice inclusions. Furthermore, it is possible to assign statistical distributions to all individual properties of the simulated ice floes: both geometrical properties, such as the size and shape of the ice fragments, as well as mechanical properties such as the ice strength.

In every ice-ice contact the pressure and frictional forces are calculated, and possible crushing and rafting processes between the ice floes are modelled. Furthermore, in the ice-structure contacts the ice crushing is taken into account, and the ice floes can fracture in bending and splitting modes against the structural interface. The other simulated loads on the structure include buoyancy, wind and current drag forces, damping loads, mooring reactions and propulsion forces.

Given initial and boundary conditions, the SIBIS simulation engine computes for each time step the dynamics of the ice and the structure in 6 DOF, normal and frictional contact forces for ice-structure and ice-ice interactions, fluid-structure and fluid-ice interactions (hydrostatics and hydrodynamics) and the stationkeeping system behaviour and response. Ice fractures are modelled dynamically, depending on the actual physical configuration of the simulated system at each time step, i.e. the failure patterns are not pre-assumed.

Throughout the simulation process the SIBIS software produces output files with loads on the structure (global and local), motions of the structure, and other relevant numerical data - for subsequent analysis and post-processing by the user. Finally, visualization of the simulation process can be performed by the SIBIS package both in real-time and after full completion of an individual simulation run.

SIBIS MODEL CALIBRATION

The SIBIS model has been calibrated against model-scale experiments of a floating drillship in managed ice conditions at the large ice tank of the Hamburg Ship Model Basin (Bonnemaire et al., 2015). A principle sketch of the corresponding numerical setup is shown in Figure 4: the vessel was moored to an underwater carriage moving forward along the basin, which was modelled with 4 static walls confining the ice cover. The simulated broken ice fields had a similar concentration and floe size distributions as the ones utilized in the model basin. A total of eight interactions performed in the ice basin were modelled numerically. This included ice covers of two different significant floe sizes, two ice thicknesses, and concentrations in the range from 70% to 90%. Special attention was paid to accurate replication and control of the initial ice floe size distributions, because it was one of the main steering parameters in the physical experiments.

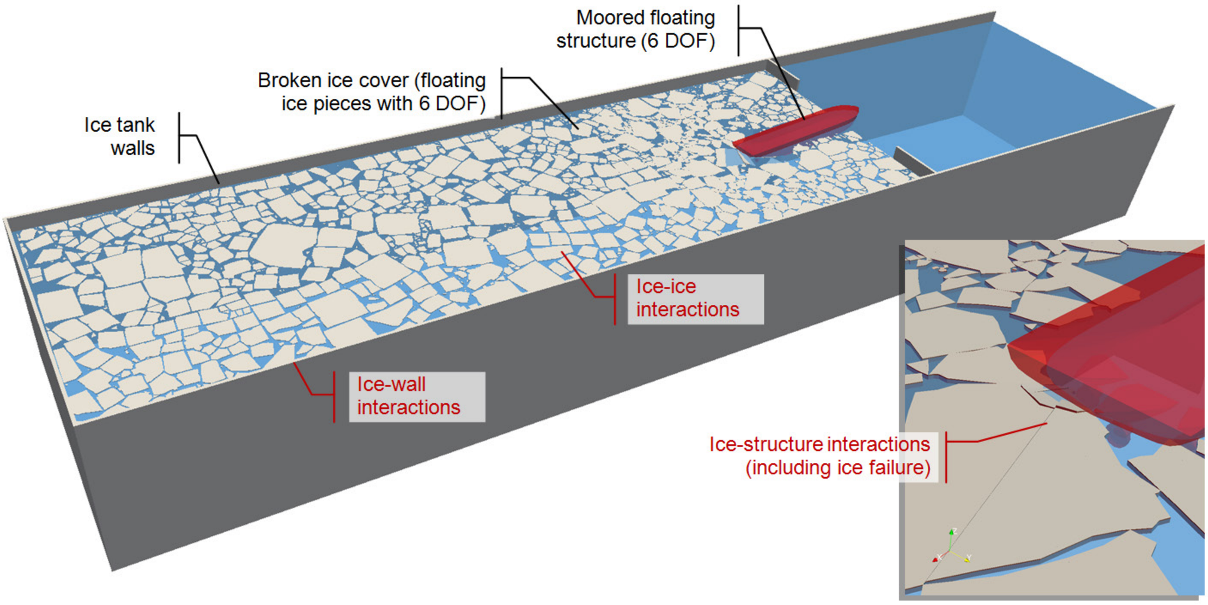

Figure 4. Principle sketch of the SIBIS numerical setup for ice basin simulations.

The outcomes of the simulations were recorded and compared with the available model-scale data. Main focus was placed on the major processes that govern the global response level:

- Response of the ice field, including mobilization of the ice field, confinement increase due to the boundary effects and interlocking effects (Figure 5);
- Ice failure modes (bending, splitting, crushing), ice accumulation and material transport processes around the structure – both in-plane and sub-surface;
- Response of the structure in different degrees of freedom;
- Loads in the mooring system.

Figure 6 shows two examples of comparisons between the achieved and simulated mooring loads. The experimental results are shown in red colour, while the numerical results are shown in blue colour. The load time series indicate that similar mooring load levels and trends are achieved along the ice basin. However, the time series differ locally. Exact replica is not expected due to the nature of interactions in broken ice. Those interactions are highly stochastic, and a small perturbation at some point may evolve into a substantially different global interaction. Furthermore, the interactions are short with just a few main oscillations. Therefore, it is challenging to compare the extreme values since several oscillations (or a longer interaction) may result in completely different extreme values.

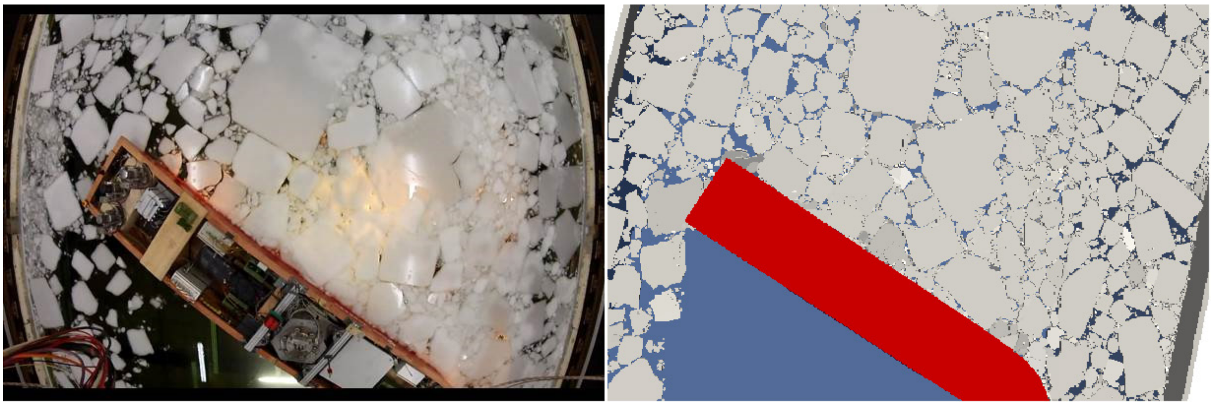

Figure 5. A comparison between ice interactions in the experiment and SIBIS simulation.

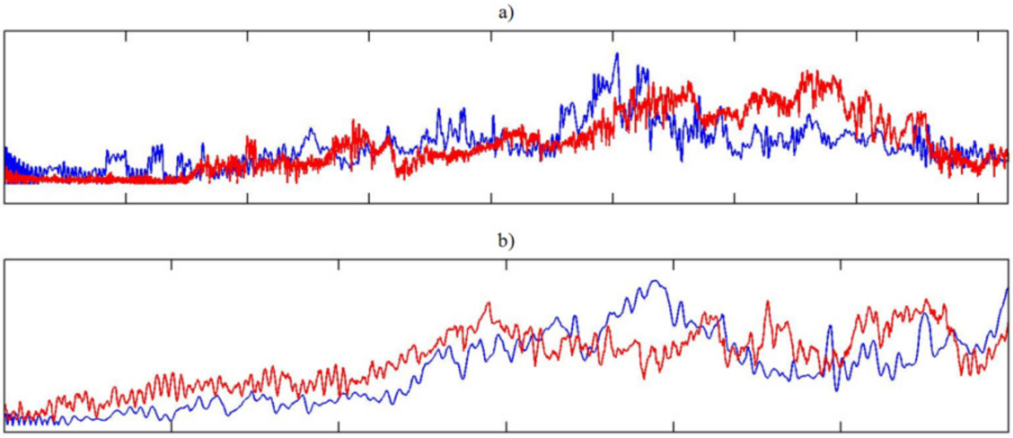

Figure 6. Comparison of the measured (in red) and simulated (in blue) mooring load time series for 2 distinct interactions: a) 90 % concentration, large floes; b) 90 % concentration, small floes. The axes in the plots are not marked due to confidentiality restrictions.

The model-scale results have also been used to calibrate the ice material accumulation and transport functionality in SIBIS. Figure 7 (middle row) qualitatively compares the simulated ice accumulation to the one achieved in the model tests (top row). Pre-broken rectangular ice pieces with a certain thickness were used in the numerical model to reproduce an ice sheet that would lead to ice accumulation. An ice basin configuration was used in SIBIS to tow the stern of the vessel through the ice field at a certain velocity, when the ice field was confined by the walls of the model tank. It can be seen in Figure 7 that the accumulation effects are quite well replicated by the SIBIS model.

SIBIS MODEL APPLICATION

After the numerical model had been calibrated against model-scale experimental data, it was applied for performance assessments of the vessel in realistic metocean conditions (Metrikin et al., 2015). First of all, the SIBIS model was used to evaluate a design change of the icebreaking stern of the vessel. In order to reduce the ice accumulations observed in the model tests, the thruster boxes were modified in an attempt to reduce the ice accumulations and cater for better ice material clearing in the stern area. The boxes were narrowed down and were extended deeper to provide more space for the ice clearing. Then, numerical simulations were performed with the SIBIS model in 180º and 165º astern configurations in 0.6 m and 1.2 m ice thicknesses, and it was verified that the modified stern has enhanced the ice clearing capabilities of the drillship (Figure 7, bottom row). Further material transport investigations could also be performed using the SIBIS model, in order to understand if the ice could be potentially transported into the moonpool of the drillship or foul its mooring lines.

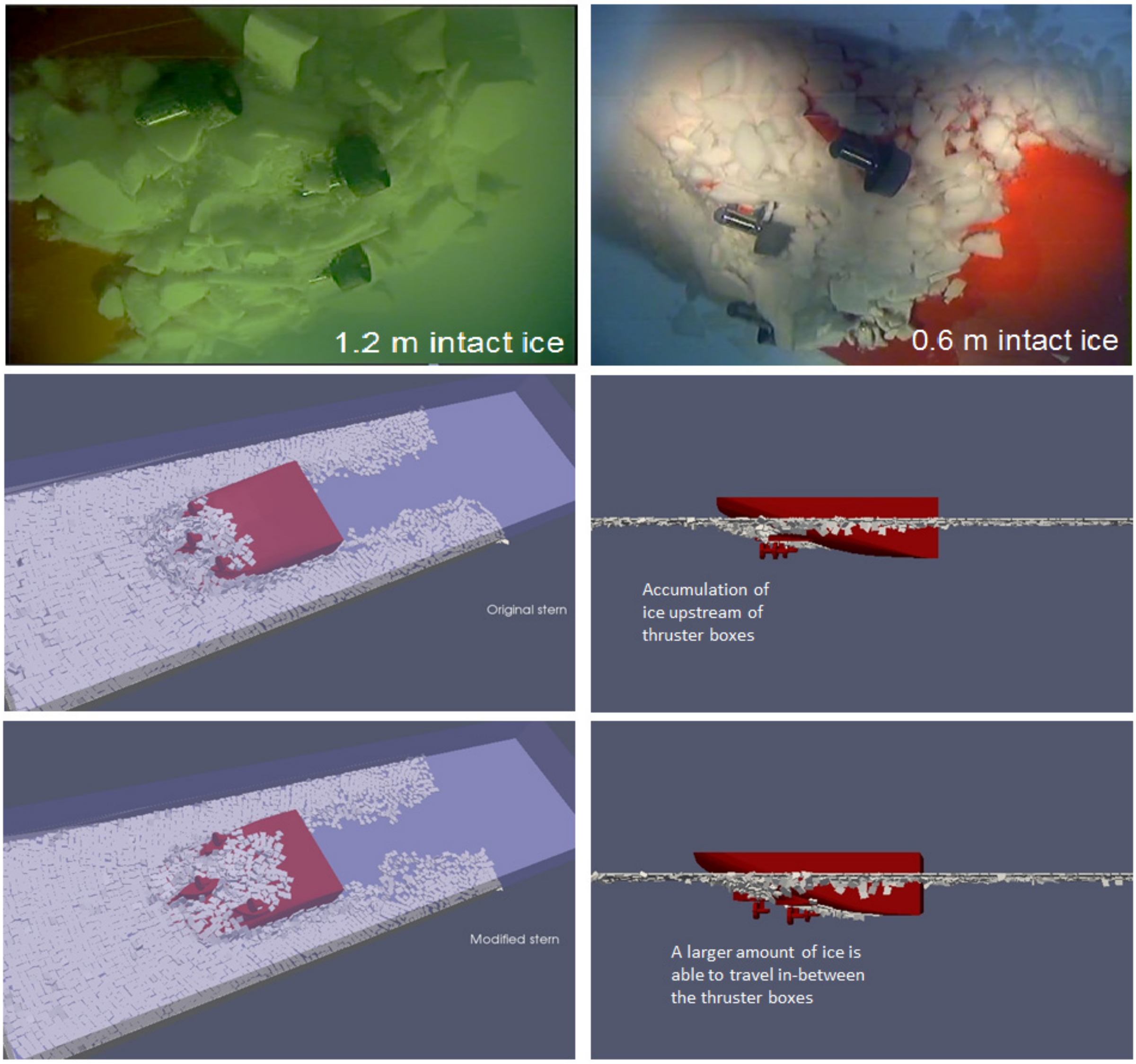

Figure 7. Measurements and simulations of the ice material accumulation and transportation processes. Top row: physical model test, middle row: SIBIS simulation with the original stern design, bottom row: SIBIS simulation with the improved stern design.

The second application of the qualified SIBIS model was to produce a mapping of the vessel's response to a set of interactions with realistic full-scale managed ice conditions, i.e. development of an M2L (Managed ice to Load) transfer function (Liferov, 2014). This included:

- Definition and modelling of a set of relevant full-scale managed ice environments;
- Simulation of the response of the hull when moored in the drifting ice fields;
- Mapping the response of the vessel to a set of ice conditions (ice floe size distributions, concentrations and thicknesses).

The outcome of the study could then be used to simulate operations at a particular geographical location, and estimate the operability and potential downtime of the drillship at that location.

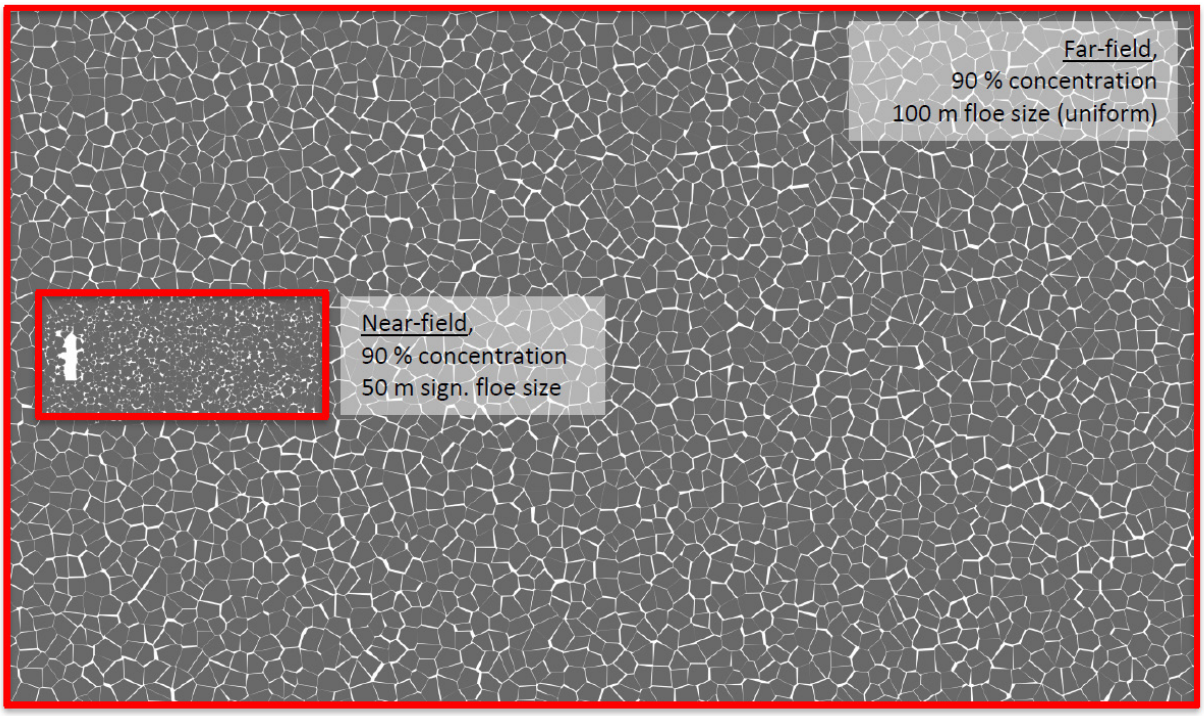

Figure 8. A full-scale managed ice field used for simulations in SIBIS.

The broken ice fields used in the simulations were divided into two parts: a near-field area of managed ice and a far-field area where the floes were unmanaged. The ice concentration was the same over the whole ice field (both near-field and far-field), ensuring a uniform confinement over the whole ice cover. An example of the utilized ice field is shown in Figure 8, where the simulation domain is 6000m long and 3500m wide, and the near-field managed ice domain dimensions are 1500m by 700m. The corresponding simulation setup in SIBIS is shown in Figure 9, and several snapshots from the dynamical simulation process are shown in Figure 10. Finally, an example of simulation results is given in Figure 11.

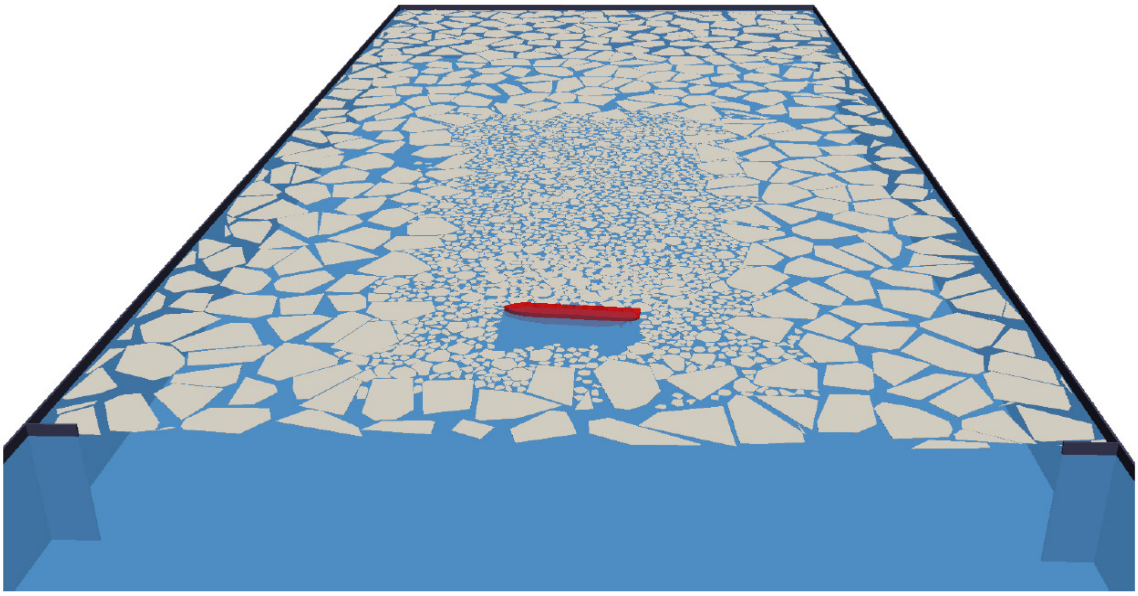

Figure 9. SIBIS simulation setup for a vessel in managed ice.

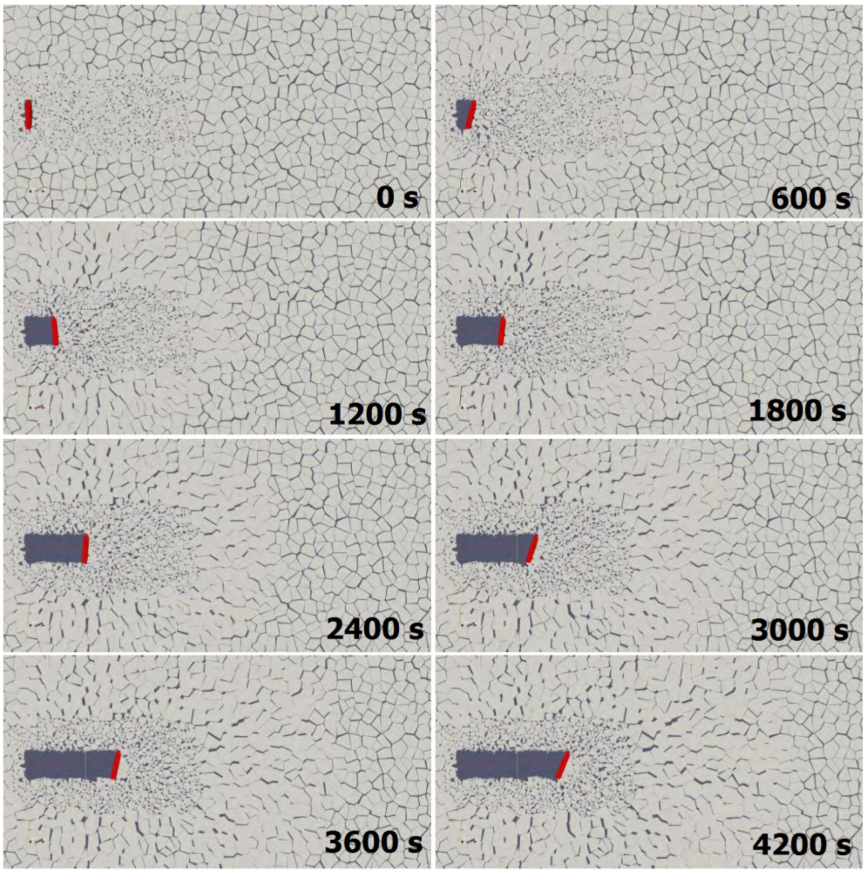

Figure 10. Bird-view snapshots from a SIBIS simulation in 90% ice concentration with 50m significant floe size and 0.5m thick ice floes (90° initial ice drift heading).

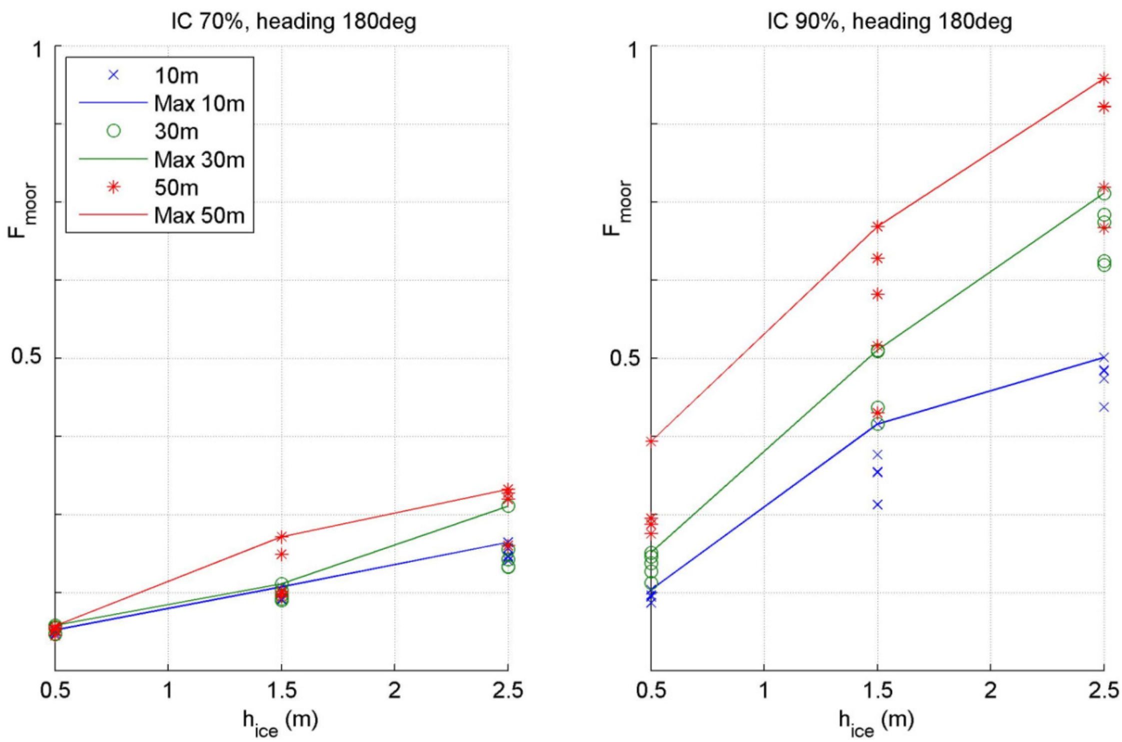

Figure 11. Maximum mooring loads (normalized) for 180° initial heading. Each dot is for one run of each scenario: ice concentration and floe size distribution are constant, but the geometrical positions of the floes are rearranged. 10m, 30m and 50m are the managed ice floe sizes. The continuous lines show the upper-bound envelopes of the mooring loads.

It can be seen in Figure 11 that the mooring loads increase almost linearly with the ice thickness. However, the load levels are 2 – 3 times higher at 90% ice concentration compared to 70% ice concentration. Furthermore, the load levels are 1.5 – 2 times larger for 50m ice floes compared to 10m ice floes. These trends are expected, and were confirmed to be in accordance with existing empirical formulations for managed ice loads on floating structures.

DISCUSSION

Interaction between a floating structure and a broken ice field is a complex process due to the highly nonlinear interdependency between the ice actions and the structural response. It is also a highly stochastic process, because the bearing capacity of the broken ice cover depends on the distribution and shapes of a large amount of individual ice fragments. Therefore, a small perturbation of an individual interaction event (e.g. rotation of an ice floe instead of fracture) may lead to a substantially different response of the ice cover in the long term, which in turn will lead to a different global action on the structure. Those properties are challenging with regards to both repeatability of a given interaction and estimation of the statistical parameters of a response time series (such as expected extremes). Therefore, a full replication of the ice-structure interaction process does not seem to be possible, and some deviations are perhaps unavoidable. Due to the stochastic character of the interactions, the measured and simulated responses should then be compared only with regards to trends, load levels and general dependencies on the structural response or the boundary conditions.

The SIBIS numerical model is a good tool for simulating such complex interactions, because it captures the dynamical behaviour of the structure in all degrees of freedom (e.g. roll and pitch angles affecting the waterline and the associated local ice-structure interaction, and the yaw angle affecting the relative ice drift direction) as well as the ice field dynamics, including compaction, interlocking, formation of accumulations, ice transport effects, fracture of ice floes, friction, fluid effects etc. However, realistic simulations require a sufficiently precise numerical replica of the broken ice field (especially with regards to the ice concentration and floe size distribution), because even slight perturbations in the ice field may lead to significant disturbances of the load and response signals (as can be seen in Figure 11). Further investigations of those perturbations and a rigorous statistical analysis of the simulation results are subject to further research work with the SIBIS model. Furthermore, image processing methods for identification and extraction of individual ice floes and representative floe size distributions (Zhang and Skjetne, 2014a, 2014b; Zhang et al., 2015) are highly relevant to the problems discussed in this paper, and should be further explored.

The main limitation of the current SIBIS model is the lack of validation against full-scale data. Therefore, there is currently an ongoing validation effort against the publically available Kulluk dataset, and additional dedicated full-scale measurements are being collected in Statoil-led expeditions and field trials for the purpose of validating SIBIS. Furthermore, the hydrodynamic model of SIBIS is currently being re-developed in order to include the added mass effects and a better numerical model for the damping loads. One of the ambitions with regards to hydrodynamics is to include functionalities for simulating waves in the broken ice field and combined wave-ice actions on offshore structures. Additionally, there is a need to develop an ice drift feature which would produce realistic motions of a broken ice field under the influence of winds and currents. With regards to ice mechanics, there is a need to develop a better brash ice model, functionality for ridge building in ice-ice contacts, and a model for consolidated ice rubble (e.g. cohesion in the keels of ice ridges). Finally, there is an on-going effort to improve the computational efficiency of the software by utilizing GPU parallelization and cloud computing technologies.

CONCLUSIONS

This paper presents a novel, independently developed numerical environment for simulating offshore operations in discontinuous ice – SIBIS (**S**imulation of **I**nteraction between **B**roken **I**ce and **S**tructures). The structure and capabilities of the software package are described in the paper, together with the input-output functionalities available to the user. Furthermore, calibrations of the numerical model against model-scale experiments of a floating drillship in broken ice conditions, described in the paper, demonstrate that SIBIS produces adequate results which can be used for preliminary performance assessments of the drillship's operability in broken ice conditions. Application examples of the calibrated model include a design change of the hull structure of the drillship, and mapping of the vessel's response to a set of interactions with realistic managed ice fields. In the latter example it is found that the global load trends, produced by SIBIS, are reasonable and in accordance with existing empirical formulations for global loads on floating structures from broken ice. Finally, some limitations of the numerical model are indicated and further development efforts are outlined.

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REFERENCES

Alawneh, S., 2014. Hyper-Real-Time Ice Simulation and Modeling Using GPGPU. PhD thesis. Memorial University of Newfoundland.

Alawneh, S., Dragt, R., Peters, D., Daley, C., G., Bruneau, S., 2015. Hyper-Real-Time Ice Simulation and Modeling Using GPGPU. IEEE Transactions on Computers. doi:10.1109/TC.2015.2409861.

Amdahl, T., H., Bjørnsen, B., Hagen, O., J., Søberg, S., R., 2014. Numerical simulations of ice loads on an Arctic Floater in managed ice. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24549, doi:10.4043/24549-MS.

Barker, A., Sayed, M., Timco, G., W., 2000. Numerical Simulations of Broken Ice Interaction with Structures. National Research Council of Canada, Canadian Hydraulics Centre Technical Report HYD-TR-050, PERD/CHC Report 9-82.

Barker, A., Sayed, M., Timco, G., W., 2002. Numerical Simulation of Ice Interaction with a Wide Cylindrical Pier. Cold Regions Engineering Conference, pp. 617-628.

Barker, A., Sayed, M., 2012. Upward- or Downward-Breaking Cones in Ice: Which One Should You Use? Cold Regions Engineering Conference, pp. 715-724.

Barker, A., Sudom, D., Sayed, M., 2014. Conical structures in ice: the roles friction, slope and shape play. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24566, doi:10.4043/24566-MS.

Bonnemaire, B., Tan, X., Serré, N., Fredriksen, A., Metrikin, I., Gürtner, A., 2015. Post-simulations of Ice Basin Tests of a Moored Structure in Broken Ice - Challenges and Solutions. Arctic Technology Conference, 23-25 March 2015, OTC paper number 25531, doi:10.4043/25531-MS.

Croasdale, K., R., Bruce J., R., Liferov, P., 2009. Sea Ice Loads Due To Managed Ice. 20th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'09). June 9-12, 2009, Luleå, Sweden.

Cundall, P., A., 1971. A computer model for simulating progressive, large-scale movements in blocky rock systems. Symposium of the International Society for Rock Mechanics, 2(8), pp. 129-136.

Daley, C., G., Alawneh, S., Peters, D., Quinton, B., W., Colbourne, D., B., 2012. GPU Modeling of Ship Operations in Pack Ice. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2012).

Daley, C., G., Alawneh, S., Peters, D., Blades, G., Colbourne, B., 2014a. Simulation of Managed Sea Ice Loads on a Floating Offshore Platform using GPU-Event Mechanics. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2014).

Daley, C., G., Alawneh, S., Peters, D., Colbourne, B., 2014b. GPU-Event-Mechanics Evaluation of Ice Impact Load Statistics. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24645, doi:10.4043/24645-MS.

Eik, K., J., Aksnes, V., Ø., 2010. Characterisation of peak loads on a moored production vessel in ice. 20th IAHR International Symposium on Ice, Lahti, Finland, June 14 to 18, 2010.

Eik, K., J., 2011. Sea-ice management and its impact on the design of offshore structures. Cold Regions Science and Technology, 65(2), 172–183. doi:10.1016/j.coldregions.2010.10.009.

Gürtner, A., Bjørnsen, B., E., Amdahl, T., H., Søberg, S., R., Teigen, S., H., 2012. Numerical Simulations of Managed Ice Loads on a Moored Arctic Drillship. Arctic Technology Conference, 3-5 December 2012, OTC paper number 23816, doi:10.4043/24549-MS.

Haase, A., Polojärvi, A., Tuhkuri, J., 2010. 3D Discrete Numerical Modelling of Conical Structure-Ice Rubble Interaction. IAHR International Symposium on Ice, pp. 330-335.

Hals, T., Jenssen, N., A., 2012. DP ice model test of arctic drillship and polar research vessel. International Conference on Offshore Mechanics and Arctic Engineering (OMAE2012), vol. 6, pp. 467–472.

Ishibashi, D., Shigihara, T., Konno, A., 2014. Experimental and Numerical Investigation of Model-Scale Collision of Ship with Ice Floe. 22nd IAHR International Symposium on Ice, pp. 495–502.

Iyerusalimskiy, A., Gu, G., Zou, J., Chianis, J., Kumar, B., Sayed, M., 2012. A conceptual study of deepwater arctic floater for year-round drilling and production. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2012).

Jenssen, N., A., Muddusetti, S., Phillips, D., Backström, K., 2009. Dynamic Positioning in Ice Conditions. Dynamic Positioning Conference 2009. Houston, Texas, USA.

Jenssen, N., A., Hals, T., Jochmann, P., Haase, A., Dal Santo, X., Kerkeni, S., Doucy, O., Gürtner, A., Støle Hetschel, S., Moslet, P., O., Metrikin, I., Løset, S., 2012. DYPIC - A Multi-National R&D Project on DP Technology in Ice. Dynamic Positioning Conference 2012. Houston, Texas, USA.

Ji, S., Li, Z., Li, C., Shang, J., 2013. Discrete element modeling of ice loads on ship hulls in broken ice fields. Acta Oceanologica Sinica, 32(11), 50–58. doi:10.1007/s13131-013-0377-2.

Ji, S., P., Li, Z., L., Huang, M., M., Wang, Y., H., Tian, Y., K., Li, Z., G., 2014. Initial concept design for a self-icebreaking container vessel in ice-covered water region. International Offshore and Polar Engineering Conference (ISOPE2014), pp. 1144-1151.

Karulin, E., B., Karulina, M., M., 2010. Performance Studies for Technological Complex Platform "Prirazlomnaya" – Moored Tanker in Ice Conditions. Ninth (2010) ISOPE Pacific/Asia Offshore Mechanics Symposium, Busan, South Korea, pp. 202–208.

Karulin, E., B., Karulina, M., M., 2011. Numerical and physical simulations of moored tanker behaviour. Ships and Offshore Structures, 6(3), 179–184. doi:10.1080/17445302.2010.544087.

Karulin, E., B., Karulina, M., M., 2013. Determination of loads on mooring system during the semisubmersible interaction with ice. International Offshore and Polar Engineering Conference (ISOPE2013), pp. 1288–1294

Karulin, E., B., Karulina, M., M., 2014. Peculiarities of Multi-Legged Platform Operation in Ice Condition. In ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering (ISOPE2014), June 8-13, 2014, San Francisco, California, USA.

Keinonen, A., J., Browne, R., Revill, C., Reynolds, A., Robbins, I., 1998. Icebreaker Characteristics Synthesis. Transport Canada Transportation Development Centre Technical Report No. TP 12812E, in 3 volumes. AKAC INC.

Kerkeni, S., Dal Santo, X., Metrikin, I., 2013a. Dynamic Positioning in Ice - comparison of control laws in open water and ice. ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013).

Kerkeni, S., Metrikin, I., Jochmann, P., 2013b. Capability Plots of Dynamic Positioning in Ice. ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2013).

Kerkeni, S., Metrikin, I., 2013. Automatic Heading Control for Dynamic Positioning in Ice. Dynamic Positioning Conference 2013, Houston, Texas, USA.

Kim, M.-C., Lee, S.-K., Lee, W.-J., Wang, J., 2013. Numerical and experimental investigation of the resistance performance of an icebreaking cargo vessel in pack ice conditions. International Journal of Naval Architecture and Ocean Engineering, 5(1), 116–131. doi:10.3744/JNAOE.2013.5.1.116.

Kim, M.-C., Lee, W.-J., Shin, Y.-J., 2014. Comparative study on the resistance performance of an icebreaking cargo vessel according to the variation of waterline angles in pack ice conditions. International Journal of Naval Architecture and Ocean Engineering, 6, 876–893. doi:10.2478/IJNAOE-2013-0219.

Kjerstad, Ø., K., Skjetne, R., 2014. Modeling and Control for Dynamic Positioned Marine Vessels in Drifting Managed Sea Ice. Modeling, Identification and Control: A Norwegian Research Bulletin, 35(4), 249–262. doi:10.4173/mic.2014.4.3.

Kjerstad, Ø., K., Metrikin, I., Skjetne, R., 2015. Description and Numerical Simulations of Dynamic Positioning in Reversing Managed Ice. 23rd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'15).

Konno, A., Mizuki, T., 2006a. On the numerical analysis of flow around ice piece moving near icebreaker hull (Second report: Application of Physically-Based Modeling to simulation of ice movement). 21st International Symposium on Okhotsk Sea & Sea Ice, pp. 74-77.

Konno, A., Mizuki, T., 2006b. Numerical Simulation of Pre-Sawn Ice Test of Model Icebreaker Using Physically Based Modeling. Proc. of the 18th IAHR International Symposium on Ice.

Konno, A., Yasuki, N., Yamamoto, K., Wako, D., Takimoto, T., Izumiyama, K., 2007. On the numerical analysis of flow around ice piece moving near icebreaker hull (Third report: comparison of simulation results with experimental results under pre-sawn ice condition). 22nd International Symposium on Okhotsk Sea & Sea Ice, pp. 29–32.

Konno, A., Yoshimoto, K., 2008. Numerical simulation of ship navigation in brash ice channels. 23rd International Symposium on Okhotsk Sea & Sea Ice, pp. 104–107.

Konno, A., 2009a. Numerical simulation of ship navigation in brash ice channels (Second report: effect of size and layer number of ice pieces). 24th International Symposium on Okhotsk Sea & Sea Ice, pp. 35–38.

Konno, A., 2009b. Resistance Evaluation of Ship Navigation in Brash Ice Channels with Physically Based Modeling. 20th International Conference on Port and Ocean Engineering under Arctic Conditions(POAC'09), Luleå, Sweden.

Konno, A., Saitoh, O., 2010. Preparation method of numerical ice channel and its evaluation for simulation of navigation in ice. 25th International Symposium on Okhotsk Sea & Sea Ice, pp. 154–159.

Konno, A., Saitoh, O., Watanabe, Y., 2011. Numerical investigation of effect of channel condition against ship resistance in brash ice channels. 21st International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'11).

Konno, A., Nakane, A., Kanamori, S., 2013. Validation of Numerical Estimation of Brash Ice Channel Resistance with Model Test. 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'13).

Lau, M., 2006. Discrete Element Modeling of Ship Manoeuvring in Ice. 18th IAHR International Symposium on Ice, pp. 25-32.

Lau, M., Ré, A., S., 2006. Performance of Survival Craft in Ice Environments. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2006).

Lau, M., Lawrence, K., P., Rothenburg, L., 2011. Discrete element analysis of ice loads on ships and structures. Ships and Offshore Structures, 6(3), 211–221. doi:10.1080/17445302.2010.544086.

Lawrence, K., P., 2009. Load Prediction for a Moored Conical Drillship in Level Unbroken Ice: A Discrete Element and Experimental Investigation. PhD thesis, University of Waterloo.

Lee, S.-G., Zhao, T., Kim, G.-S., Park, K.-D., 2013. Ice resistance test simulation of arctic cargo vessel using FSI analysis technique. 23rd International Offshore and Polar Engineering Conference (ISOPE 2013), pp. 1162-1168.

Liferov, P., 2014. Station-Keeping in Ice – Normative Requirements and Informative Solutions. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24580, doi:10.4043/24580-MS.

Liu, L., Zhan, D., Spencer, D., Molyneux, D., 2010. Pack ice forces on floating offshore oil and gas exploration systems. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2010).

Lobanov, V., A., 2011. Evaluation of Ice Propulsion Ability of Ship by Numerical Methods (in Russian). Differential Equations and Control Processes, (1), 34-47.

Lubbad, R., Løset, S., 2011. A numerical model for real-time simulation of ship–ice interaction. Cold Regions Science and Technology, 65(2), 111–127. doi:10.1016/j.coldregions.2010.09.004.

Lubbad, R., Løset, S., 2015. Time Domain Analysis of Floe Ice Interactions with Floating Structures. Arctic Technology Conference, 23-25 March 2015, OTC paper number 25517, doi:10.4043/25517-MS.

Metrikin, I., Lu, W., Lubbad, R., Løset, S., Kashafutdinov, M., 2012a. Numerical Simulation of a Floater in a Broken-Ice Field: Part I - Model Description. ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2012).

Metrikin, I., Borzov, A., Lubbad, R., Løset, S., 2012b. Numerical Simulation of a Floater in a Broken-Ice Field: Part II - Comparative Study of Physics Engines. ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2012).

Metrikin, I., Løset, S., Jenssen, N., A., Kerkeni, S., 2013. Numerical Simulation of Dynamic Positioning in Ice. Marine Technology Society Journal, 47(2), 14–30. doi:10.4031/MTSJ.47.2.2.

Metrikin, I., Løset, S., 2013. Nonsmooth 3D Discrete Element Simulation of a Drillship in Discontinuous Ice. 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'13).

Metrikin, I., 2014. A Software Framework for Simulating Stationkeeping of a Vessel in Discontinuous Ice. Modeling, Identification and Control: A Norwegian Research Bulletin, 35(4), 211–248. doi:10.4173/mic.2014.4.2.

Metrikin, I., Kerkeni, S., Jochmann, P., Løset, S., 2015. Experimental and Numerical Investigation of Dynamic Positioning in Level Ice. Journal of Offshore Mechanics and Arctic Engineering, 137(3), pp. 031501.

Metrikin, I., Teigen, S., H., Gürtner, A., Uthaug, E., S., Sapelnikov, D., Ervik, Å., Fredriksen, A., Lundamo, T., Bonnemaire, B., 2015. Experimental and Numerical Investigations of a Ship-Shaped, Turret-Moored Floating Structure in Intact and Managed Sea Ice Conditions. Arctic Technology Conference, 23-25 March 2015, OTC paper number 25528, doi:10.4043/25528-MS.

Millan, J., Wang, J., 2011. Ice Force Modeling for DP Control Systems. Dynamic Positioning Conference 2011. Houston, Texas, USA.

Molyneux, D., Liu, L., Zhan, D., Reid, G., 2012a. Ice Loads on a Moored Floating Production Unit. 10th International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2012).

Molyneux, D., Spencer, D., Liu, L., Zhan, D., 2012b. Simulation of Ship Performance in Ice Using a Discrete Element Method. Ice Class Ships Conference (The Royal Institution of Naval Architects.

O'Brien, M., 2004. DECICE and its Applications to Ice-Ship Interactions. National Research Council of Canada, Institute for Ocean Technology Report Number LM-2004-36.

Paavilainen, J., Tuhkuri, J., Polojärvi, A., 2006. Discrete Element Simulation of Ice Pile-Up Against an Inclined Structure. 18th IAHR International Symposium on Ice, Sapporo, Japan, pp. 177–184.

Paavilainen, J., Tuhkuri, J., Polojärvi, A., 2009. 2D combined finite-discrete element method to model multi-fracture of beam structures. Engineering Computations: International Journal for Computer-Aided Engineering, 26(6), 578–598. doi:10.1108/02644400910975397.

Paavilainen, J., Tuhkuri, J., Polojärvi, A., 2010. Rubble pile formation against an inclined structure – analysis of simulation results. 20th IAHR International Symposium on Ice. Lahti, Finland, June 14 to 18, 2010.

Paavilainen, J., Tuhkuri, J., Polojärvi, A., 2011. 2D numerical simulations of ice rubble formation process against an inclined structure. Cold Regions Science and Technology, 68(1-2), 20–34. doi:10.1016/j.coldregions.2011.05.003.

Paavilainen, J., Tuhkuri, J., 2012. Parameter effects on simulated ice rubbling forces on a wide sloping structure. Cold Regions Science and Technology, 81, 1–10. doi:10.1016/j.coldregions.2012.04.005.

Paavilainen, J., 2013. Factors affecting ice loads during the rubbling process using a 2D FE-DE Approach. PhD thesis, Aalto University.

Paavilainen, J., Tuhkuri, J., 2013. Pressure distributions and force chains during simulated ice rubbling against sloped structures. Cold Regions Science and Technology, 85, 157–174. doi:10.1016/j.coldregions.2012.09.005.

Palmer, A., C., Croasdale, K., R., 2013. Arctic Offshore Engineering. World Scientific Publishing Co. Pte. Ltd.

Park, K., D., Chung, Y., K., Jang, Y., S., Kim, H., S., Molyneux, D., 2011. Development of hull forms for a 190,000 DWT icebreaking ore carrier. International Conference on Offshore Mechanics and Arctic Engineering (OMAE2011).

Polojärvi, A., Tuhkuri, J., 2009. 3D discrete numerical modelling of ridge keel punch through tests. Cold Regions Science and Technology, 56(1), 18–29. doi:10.1016/j.coldregions.2008.09.008.

Polojärvi, A., Tuhkuri, J., 2010. Modelling Ridge Keel Freeze Bonds in Finite-Discrete Element Method Simulations. 20th IAHR International Symposium on Ice. Lahti, Finland, June 14 to 18, 2010.

Polojärvi, A., Tuhkuri, J., Korkalo, O., 2012. Comparison and analysis of experimental and virtual laboratory scale punch through tests. Cold Regions Science and Technology, 81, 11–25. doi:10.1016/j.coldregions.2012.04.008.

Polojärvi, A., Tuhkuri, J., 2013. On modeling cohesive ridge keel punch through tests with a combined finite-discrete element method. Cold Regions Science and Technology, 85, 191–205. doi:10.1016/j.coldregions.2012.09.013.

Polojärvi, A., 2013. Sea ice ridge keel punch through experiments: model experiments and numerical modeling with discrete and combined finite-discrete element methods. PhD thesis, Aalto University.

Polojärvi, A., Tuhkuri, J., 2014. 3D DEM for Freeze Bonded Ice Rubble Consisting of Polyhedral Blocks. 22nd IAHR International Symposium on Ice, pp. 195–202.

Polojärvi, A., Tuhkuri, J., Pustogvar, A., 2015. DEM simulations of direct shear box experiments of ice rubble: Force chains and peak loads. Cold Regions Science and Technology, 116, 12–23. doi:10.1016/j.coldregions.2015.03.011.

Quinton, B., W., 2006. DECICE Implementation of Ship Performance in Ice: a Summary Report. National Research Council of Canada, Institute for Ocean Technology Report Number SR-2006-06.

Ranta, J., Tuhkuri, J., Polojärvi, A., Paavilainen, J., 2014. Statistical Reconstruction of Peak Ice Load Data Based on 2D Combined Finite-Discrete Element Method Simulations of Ice Interactions Against Inclined Wall. 22nd IAHR International Symposium on Ice, pp. 426–433.

Sayed, M., 1997. Discrete And Lattice Models of Floating Ice Covers. International Offshore and Polar Engineering Conference (ISOPE1997), pp. 428-433.

Sayed, M., Barker, A., 2011. Numerical Simulations of Ice Interaction with a Moored Structure. Arctic Technology Conference, 7-9 February 2011, OTC paper number 22101, doi:10.4043/22101-MS.

Sayed, M., Kubat, I., 2011. Forces on ships transiting pressured ice covers. International Offshore and Polar Engineering Conference (ISOPE2011), pp. 1087-1092.

Sayed, M., Kubat, I., Wright, B., Iyerusalimskiy, A., Phadke, A., C., Hall, B., K., 2012a. Numerical Simulations of Ice Interaction with a Moored Structure. 10th International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2012).

Sayed, M., Kubat, I., Wright, B., 2012b. Numerical Simulations of ice forces on the Kulluk: the role of ice confinement, ice pressure and ice management. Arctic Technology Conference, 3-5 December 2012, OTC paper number 23823, doi:10.4043/23823-MS.

Sayed, M., Kubat, I., Wright, B., Millan, J., 2014a. Numerical Simulations of Ice Forces on Moored and Thruster-Assisted Drillships. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24647, doi:10.4043/24647-MS.

Sayed, M., Kubat, I., Wright, B., Millan, J., 2014b. Numerical Modelling of the Stationkeeping of Drillships in Ice. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2014).

Sayed, M., Kubat, I., Watson, D., Wright, B., Gash, R., Millan, J., 2015. Simulations of the Stationkeeping of Drillships under Changing Direction of Ice Movement. Arctic Technology Conference, 23-25 March 2015, OTC paper number 25565, doi:10.4043/25565-MS.

Scibilia, F., Metrikin, I., Gürtner, A., Teigen, S., H., 2014. Full-Scale Trials and Numerical Modeling of Sea Ice Management in the Greenland Sea. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24643, doi:10.4043/24643-MS.

Selvadurai, A., P., S., 2009. Fragmentation of Ice Sheets during Impact. CMES: Computer Modeling in Engineering & Sciences, 52(3), 259–278. doi:10.3970/cmes.2009.052.259.

Septseault, C., Béal, P.-A., Le Yaouanq, S., Dudal, A., Roberts, B., 2014. A New Ice Simulation Tool Using a Multi-Model Program. Arctic Technology Conference, 10-12 February 2014, OTC paper number 24644, doi:10.4043/24644-MS.

Septseault, C., Béal, P.-A., Le Yaouanq, S., Dudal, A., Roberts, B., 2015. Update on a New Ice Simulation Tool using a Multi-Model Program. Arctic Technology Conference, 23-25 March 2015, OTC paper number 25591, doi:10.4043/25591-MS.

Spencer, D., Molyneux, D., 2009. Predicting Pack Ice Loads on Moored Vessels. Ice Class Vessels Conference (ICSOT 2009), Busan, Korea.

Sun, S., Shen, H. H., 2012. Simulation of pancake ice load on a circular cylinder in a wave and current field. Cold Regions Science and Technology, 78, 31–39. doi:10.1016/j.coldregions.2012.02.003.

Tuhkuri, J., 2005. Discrete Element Simulations in Ice Engineering. 18th Nordic Seminar on Computational Mechanics.

Vachon, G., Sayed, M., Kubat, I., 2012. Methodology for determination of ice management efficiency. 10th International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2012).

Vroegrijk, E., A., J., 2012. Application of the Discrete Element Method (DEM) on ship-ice interaction. 10th International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2012).

Wang, B., Daley, C., G., Sayed, M., Liu, J., 2010. Global Ice Loads on Arctic Drillships. International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH 2010). Paper No. ICETECH10-120-RF.

Wang, J., Derradji-Aouat, A., 2010. Ship Performance in Broken Ice Floes - Preliminary Numerical Simulations. NRC Institute for Ocean Technology Report TR-2010-24.

Wang, J., Derradji-Aouat, A., 2011. Numerical Assessment for Stationary Structure (Kulluk) in Moving Broken Ice. 21st International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'11).

Watanabe, Y., Konno, A., 2011. Investigation of effect of flow and channel condition against brash ice channel resistance. 26th International Symposium on Okhotsk Sea & Sea Ice, pp. 103–109.

Woolgar, R., C., Colbourne, D., B., 2010. Effects of hull-ice friction coefficient on predictions of pack ice forces for moored offshore vessels. Ocean Engineering, 37(2-3), 296–303. doi:10.1016/j.oceaneng.2009.10.003.

Wright, B., 1999. Evaluation of Full Scale Data for Moored Vessel Station-keeping in Pack Ice (With Reference to Grand Banks Development). PERD/CHC Report 26-200. B. Wright and Associates Ltd.

Zhan, D., Agar, D., He, M., Spencer, D., Molyneux, D., 2010. Numerical Simulation of Ship Maneuvering in Pack Ice. 29th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2010).

Zhan, D., Molyneux, D., 2012. 3-Dimensional Numerical Simulation of Ship Motion in Pack Ice. ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2012).

Zhang, Q., Skjetne, R.. 2014a. Image Processing for Identification of Sea-Ice Floes and the Floe Size Distributions. IEEE Transactions on Geoscience and Remote Sensing, doi:10.1109/TGRS.2014.2366640.

Zhang, Q., Skjetne, R., 2014b. Image Techniques for Identifying Sea-Ice Parameters. Modeling, Identification and Control: A Norwegian Research Bulletin, 35(4), 293–301. doi:10.4173/mic.2014.4.6.

Zhang, Q., Skjetne, R., Metrikin, I., Løset, S., 2015. Image processing for ice floe analyses in broken-ice model testing. Cold Regions Science and Technology, 111, 27–38. doi:10.1016/j.coldregions.2014.12.004.

Østhus, V., 2014. Robust Adaptive Control of a Surface Vessel in Managed Ice Using Hybrid Position- and Force Control, MSc thesis, Norwegian University of Science and Technology.