Proceedings of the 25th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2019, Delft, The Netherlands

Analysis of Oden Icebreaker Performance in Level Ice using Simulator for Arctic Marine Structures (SAMS)

Nauman Raza[1], Marnix van der Berg[1], Wenjun Lu[1], Raed Lubbad[1]
[1] Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT

The Simulator for Arctic Marine Structures (SAMS) is used to model the performance of the icebreaker Oden in level ice. In particular, we use SAMS to perform a series of simulations of Oden transiting with constant headings and speeds in level ice. The simulations cover a wide range of ship velocities and ice thicknesses. The results are ice resistance curves, i.e., ice resistance as a function of the ship speed, for the different ice thicknesses. We then use the numerically simulated ice resistance curves together with the full-scale net-thrust curve of Oden from the literature to derive the relationship between the ice thickness and the maximum velocity of Oden, i.e., the h-v curve of Oden. We compare the simulated h-v curve of Oden with the full-scale h-v curve presented in the literature and show that the results are favorable. Moreover, we investigate the sensitivity of the simulation results to input parameters such as friction and form drag coefficients.

KEY WORDS: SAMS; Ice Resistance; Performance Curve; Form Drag Coefficient; Friction Coefficient

INTRODUCTION

The increase in demand for energy and the possibility of using the Northern Sea Route for transport are the main drivers for research to understand the maneuverability of ships in ice-infested waters. For a ship (or an icebreaker) to advance safely in ice, it should have an adequate propulsion power to overcome the ice resistance and a sufficiently strong hull to withstand the ice loads. The term ice resistance refers to the time average of the longitudinal component (i.e., the component in the negative surge direction) of the global ice load, see Varsta (1989) and Riska (2010). The performance of ships in ice is often characterized by their performance curves (h-v curve) which represents the maximum speed that they can attain as a function of ice thickness.

Icebreaker operations in an ice field are categorized into two modes, namely ‘continuous-mode icebreaking’ and ‘ramming-mode icebreaking’. In the continuous-mode, the icebreaker moves at a constant speed without stopping. In the ramming mode, the icebreaker rams through ice by a series of charges. Continuous mode icebreaking is preferred over ramming in most scenarios because it is faster and more fuel efficient. In continuous icebreaking mode, as ship sails through level ice, different forces act on the ship hull. These forces can be subdivided as breaking forces (crushing and bending), forces due to ice floe rotation, submergence forces and sliding forces.

Puntigliano (2003) finds that forces from the sliding phase can be up to 65% of the total ice resistance. The ice forces in the sliding phase are mainly caused by the inertia of the broken ice, hydrodynamic drag forces on the broken ice pieces and by ice-ice and ice-structure friction. Force due to form drag depends on the shape of the broken ice floes and it follows the quadratic drag equation. These forces are higher for the floes with a larger cross section and higher relative velocity. The ice-ice and ice-structure friction force in the sliding phase is dependent on the material properties, the sliding velocity and the surface roughness. The form drag coefficient and the ice-structure friction coefficient are among the key parameters in defining the magnitude of forces in the sliding phase of ice. It is difficult to accurately measure these parameters in a full scale scenario. In addition, the value of the form drag and ice-structure friction coefficient is dependent on environmental parameters such as the ice thickness and the ambient temperature. Therefore, experimental data are usually used to tune numerical models to the representative value of form drag and ice-structure friction coefficients.

Many researchers have adopted different analytical, numerical or experimental approaches to study level ice interaction with ship/marine structures. Lewis and Edwards (1970), Enkvist et al. (1979) and Kotras et al. (1983) studied the interaction of level ice breaking with an icebreaker and classified the process into phases including ice breaking, ice rotation, sliding of broken ice against the surface and clearing. Lindqvist (1989), Keinonen et al. (1996) and Riska et al. (1997) performed full-scale measurements on icebreakers and developed analytical and empirical formulas for the ice resistance calculation. Daley (1999) presented analytical formulas to calculate ice collision forces based on a relationship between indentation energy and kinetic energy. Spencer and Jones (2001) introduced three main ice resistance terms, namely breaking resistance, buoyancy resistance and clearing resistance.

Numerical models of the interaction process can be used in combination with model-scale tests and full-scale measurements to enhance the understanding of the ice-ship interaction process. Since numerical simulations are easier and cheaper to execute than model-scale tests, a wider range of conditions can be simulated. Wang (2001) adopted a three continuum processes, which includes crushing, bending and rubble formation, and considered a simplified framework of nested discrete events. In order to simulate the contact between level ice and the structure, a geometric grid method was utilized. Ice loads were numerically computed by considering the mechanics behind ice crushing and bending while failing. Nguyen et al. (2009) and Su et al. (2010) proposed models with 3-degrees of freedom for ship-ice interaction. The studies considered breaking of ice as the main reason behind sway and yaw movements of the ship and surge motion was thought to be caused by the remaining ice load components. Lubbad & Løset (2011) presented a numerical model for real-time simulation of ship-ice interactions. They developed and used analytical closed-form solutions to model the ice breaking processes. In addition, they represented ice floes as 3 dimensional bodies with 6 degrees of freedom, solved the equations of motion of the ship and all ice floes, and estimated the ice-ice and ship-ice contact forces. More recently, Tan et al. (2013) proposed a model that is capable of incorporating ship roll, pitch and heave motions in the process of icebreaking.

In 2017, Arctic Integrated Solutions AS (ArcISo), a spin-off company from NTNU, released a numerical model for the analysis of offshore and coastal structures in Arctic conditions. The model is based on research that was performed during the SAMCoT (Centre for Research-based Innovation – Sustainable Arctic Marine and Coastal Technology). The model is known as Simulator for Arctic Marine Structures (SAMS). Lubbad et al. (2018) described the use of SAMS in a broken ice field, which is modelled as an ensemble of discreet ice bodies, and validated the results with the full-scale data from the Oden Arctic Technology Research Cruise (2015). The results of the numerical model conform to the full-scale tests. This paper mainly focuses on the assessment of SAMS for level ice by constructing the performance curve of Oden. A sensitivity analysis is performed to check the influence of form drag and friction coefficients on the model outcome. The results of the model are validated by comparison to the full-scale test presented by Johansson and Liljestrom (1989).

MODEL SET-UP

SAMS is a three dimensional (3D) multi-body time-domain simulator designed for ice-structure interaction. Ice action on structures/ships is a result of interaction between dynamic bodies. Hydrostatic forces are calculated from the submerged geometry of each body. Hydrodynamic drag forces are determined using the local velocity and user-specified drag coefficients. Collision detection is performed in each time step. Contact forces are solved using the non-smooth discrete element method, in which contact compliance has been introduced. The contact compliance parameters are computed using the assumption that local ice crushing will occur at ice-ice and ice structure contacts. Contact compliance parameters in SAMS are determined using the exact contact geometry and the material properties of sea ice (van den Berg et al., 2018). As per Lu et al. (2018), resulting contact forces are utilized to model ice floe failure using analytical solutions for splitting and bending failure. The floe shape and size is taken into account in determining the splitting force and direction.

In this study, the ice-structure interaction between the icebreaker Oden and a semi-infinite level ice sheet is simulated using SAMS. Oden is sailing in a continuous breaking mode with a constant velocity. Only motion in surge direction is considered and the ship model is fixed in all other degrees of freedom. Initially, to plot the performance curve of Oden, a set of simulations with variable ice thickness and ship speed is carried out. The simulated combinations are marked in green in Table 1. The properties of the ice field are presented in Table 2. A water density of 1005 kg/m^3 is considered along with skin friction coefficient of 0.005 at the ice-fluid interface. The Influence of the form drag coefficient on the calculation of hydrodynamic forces on ice floes is checked by using variable values of this coefficient in the out-of-plane direction of these floes. In the ice floes in-plane directions, a constant value of 0.1 is used. The simulation length is determined based on the time needed for the mean value of the ice load to converge to a constant value. Figure 1 presents a simulation outcome showing the time series of the cumulative mean ice resistance and its convergence towards a constant value. For each simulation, such time series are developed and a stable ice resistance value is determined. These ice resistance values are further utilized for the construction of the performance curve. The cumulative mean is calculated as follows;

$$\bar{F}_{x:N} = \frac{\sum_{i=1}^{N} F_{x;i}}{N} \quad (1)$$

Where, N is the number of time steps and $F_{x;i}$ is the total ice load on the structure in surge direction in time step i.

Table 1: Combinations of ice thicknesses and ship velocities that were simulated

Ship Velocity (m/s)	Ice thickness (m)				
	0.2	0.4	0.6	0.8	1.0
3.0					
4.0					
5.0					
6.0					
7.0					
8.0					

Table 2: Physical properties of the ice field

Parameter	Units	Value
Ice Density	kg/m^3	910
Compressive Strength	MPa	2.0
Young's Modulus	GPa	5.0
Poisson's Ratio	-	0.3
Fracture Toughness	kPa $\sqrt{m}$	150
Flexural Strength	kPa	500
Tensile Strength	kPa	500

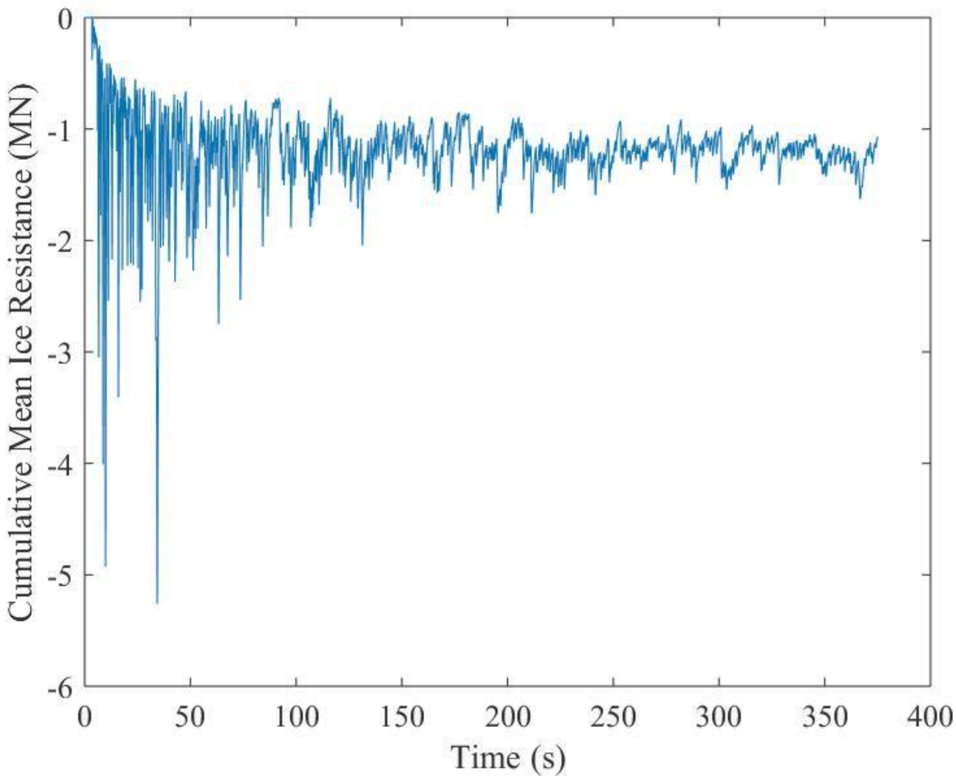

Figure 1: Time series of the cumulative mean ice resistance

SENSITIVITY ANALYSIS

Ice-structure friction has been studied extensively in the last decades, but studies on ice form drag are very limited. Lu et al. (2014) studied the interaction of level ice with wide sloping structures and concluded that the ice-structure friction coefficient has a significant effect on the ice action. Evan et al. (1976), Akkok et al. (1987) and Baurle et al. (2007) presented friction models, which require the real contact area and distribution, amount and the size of the contact as an input for the calculations of forces due to friction. Tsarau et al. (2016) suggests that a number of processes contributes to the total drag force and it is practically impossible to model all of them for an arbitrary ice floe in a random situation.

Difficulties in the direct measurement of the real contact area, the amount and size of broken ice floes and the ice floe distribution makes the determination of form drag and ice-structure friction coefficients difficult and most of the time impossible. However, these factors are highly influential to the ice resistance. Therefore, approximations are often used in numerical models in combination with a sensitivity analysis and comparison with experimental data to validate the model. A similar approach is used in this study. A sensitivity analysis is performed for a range of friction and form drag coefficients using the values taken from literature. Based on the parameters defined in Table 3, performance curves are plotted and compared with full-scale performance curves of Oden from Johansson and Liljestrom (1989).

Table 3: Input combinations of form drag coefficient and friction coefficient

Combination	Form Drag Coefficient	Friction Coefficient
Config-1	0.5	0.15
Config-2	0.3	0.05
Config-3	0.3	0.15
Config-4	0.3	0.25
Config-5	0.1	0.15
Config-6	0.1	0.20
Config-7	0.1	0.25

NET THRUST AND PERFORMANCE CURVE

A ship sailing in ice experiences thrust forces, open water resistance and ice resistance. Net thrust is defined as the thrust available to overcome ice resistance. Performance of any icebreaker in level ice is a function of the net thrust and the ice resistance. Figure 2 presents a flow chart indicating the procedure of the simulations carried out for the study. The overall results of the simulation are plotted in Figure 3, which presents the net thrust curve of Oden in light blue colour, based on the experimental results of the Johansson and Liljestrom (1989) study. The net thrust is largest at zero velocity, where it is equal to the bollard pull. With the increase of speed, the net thrust decreases, and around 8.5 m/s it becomes zero, which is the maximum open water speed of Oden. In addition to the thrust curve, Figure 3 also shows ice resistance curves at various ice thicknesses (0.2m – 1m) as obtained from SAMS. A total of 140 simulations have been carried out for all the combinations of ice thicknesses and ship velocities defined in Table 1 and for the seven configrations of form drag and friction coefficients presented in Table 3. For each of the combinations of form drag and friction coefficient, 20 time-domain simulations are performed. Each point on the ice resistance curve of a specific ice thickness represents the mean load as predicted by a simulation with one of the parameter combinations defined in Table 1 and Table 3. Seven different configurations of simulations are defined based on the parameters in Table 1 and Table 3 in Figure 2. The figure shows the procedure for only config-3 of simulations but the same procedure is adopted for all configurations (config-1 to config-7).

It can be seen from Figure 3 that the ice resistance increases with the increase in speed and ice thickness. The ice resistance from thin ice is lower because the ice breaking load, the inertial resistance, and the drag resistance is lower. In addition, the forces in the sliding phase depend on the ice coverage of the ship hull while sliding. Myland & Ehlers (2019) conducted model tests and concluded that ice hull coverage increases with ice thickness. They also concluded that the increase of ice resistance is associated with the increased ice coverage and ice thickness. Form drag forces on the thicker ice also tend to be higher due to a higher presented cross sectional area of the ice floe and the ice rubble. Figure 4 presents the bottom view of Oden, showing the ice coverage and clearance of broken ice in 0.2 m and 1.0 m thick ice, as it occurs in the numerical simulations. We observe larger ice rubble blocks and more ice rubble under the ship bottom in the simulation with 1.0 m thick ice, which contributes to the higher ice resistance.

The propulsion speed at which the ice resistance curve of a specific ice thickness intersects the net thrust curve is the maximum speed that the icebreaker can attain in that specific ice thickness. For a higher ice thickness, this maximum speed is lower because of the increased ice resistance. These speeds are marked as $v_{0.2}$ to v_1 in the Figure 3 on horizontal axis. These combinations of ice thickness and propulsion speed are utilized to plot the performance curve (h-v curve) of the icebreaker. For one combination of form drag and friction coefficients, five values of ship velocities are determined corresponding to the simulated ice thickness. This procedure is repeated for all the combinations of form drag and friction coefficients indicated in Table 3.

Figure 5 presents the performance curves plotted for the combination of velocities and ice thicknesses obtained from Figure 3 for different combinations of form drag and friction coefficients. The values of the numerical model results are compared with the performance curve obtained from full-scale tests by Johansson and Liljestrom (1989).

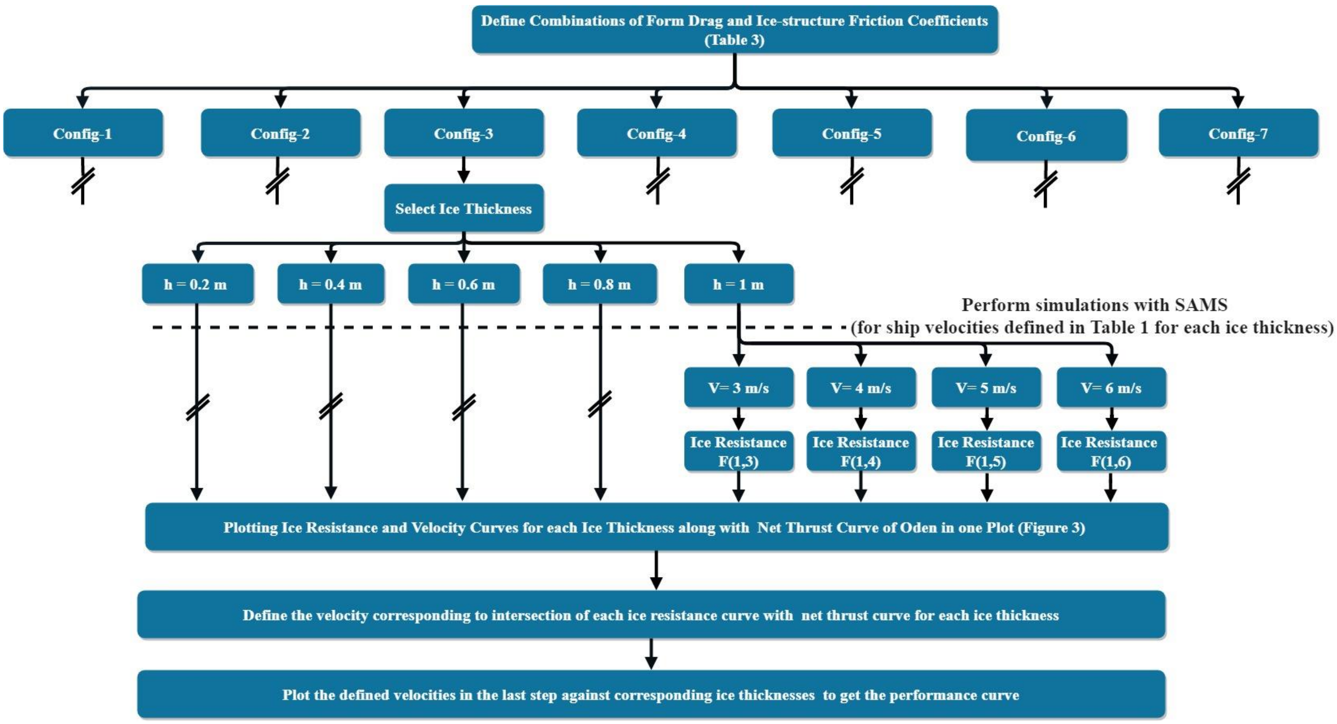

Figure 2: Flow chart of simulation procedure for SAMS

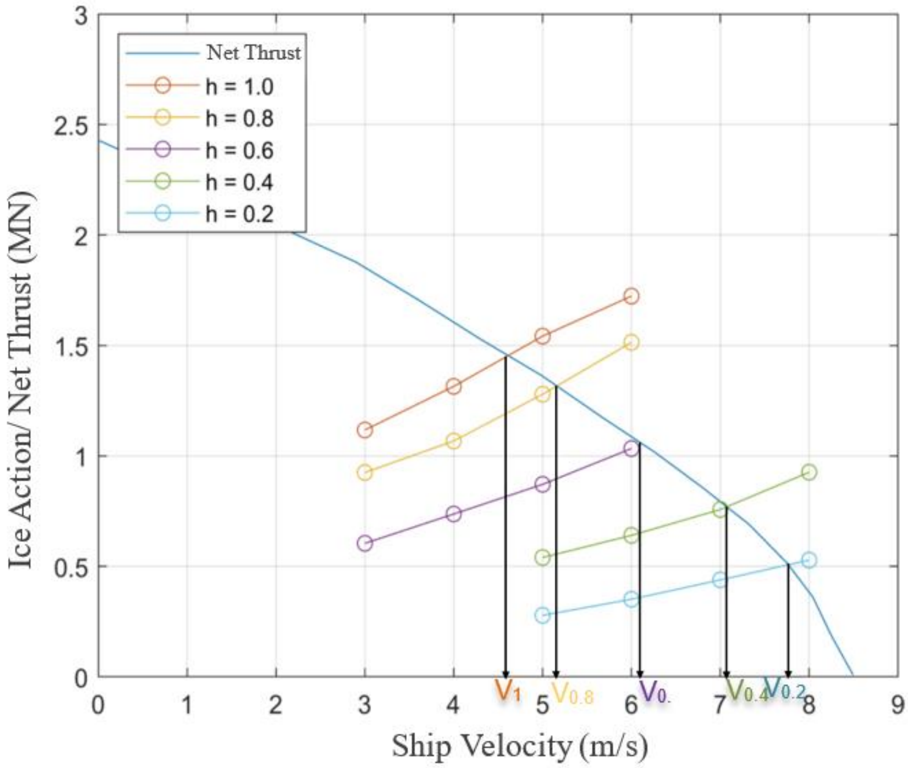

Figure 3: Net thrust and ice resistance curve(s)

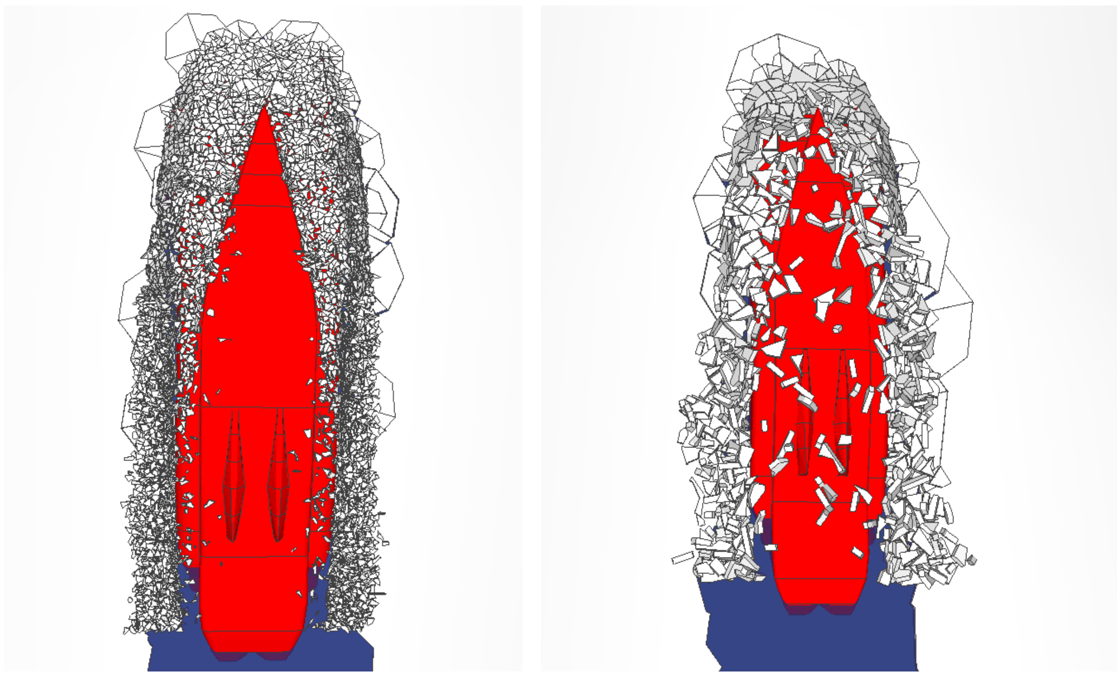

Figure 4: Bottom view of ice rubble for 0.2m thick ice (left) and bottom view of ice rubble for 1m thick ice (right)

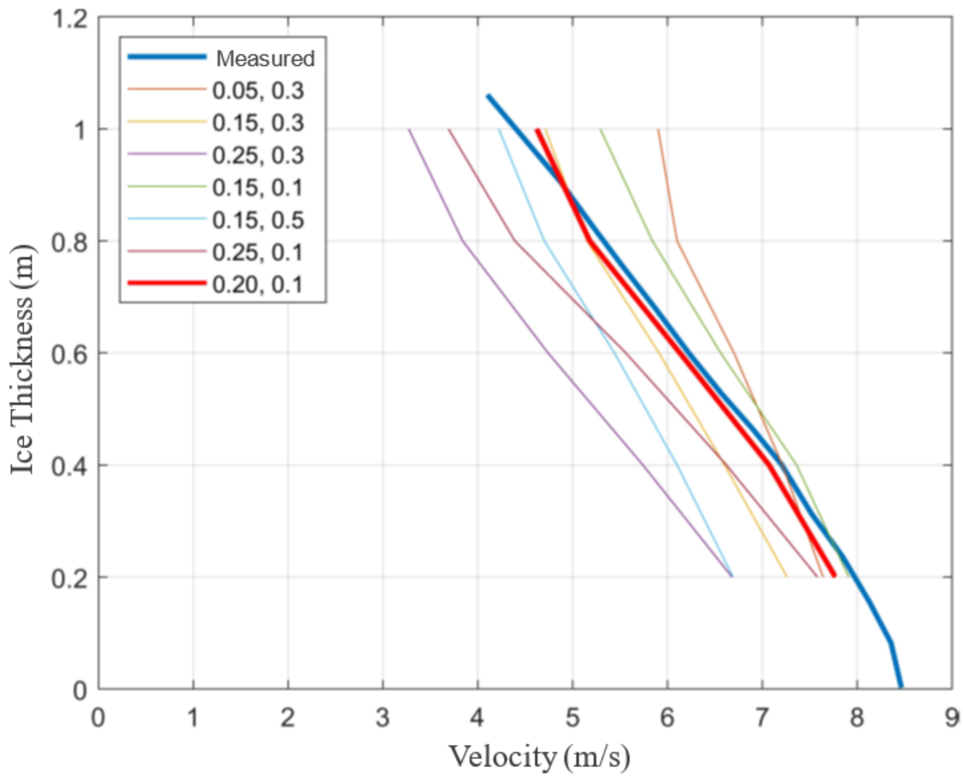

Figure 5: Performance curves resulting from the numerical simulations compared to the measured performance curve.

DISCUSSION

Figure 5 indicates that the h-v curve resulting from SAMS is close to the full-scale h-v curve when using a ship-ice friction coefficient of 0.2 and a form drag coefficient of 0.1 to calculate hydrodynamic forces on ice floes in their out-of-plane direction. Low friction coefficient values along with a high form drag coefficient (combo-2, in Table 3) indicate very high performance of the icebreaker attaining a velocity of up to 6 m/s in 1.0 m thick ice. However, it deviates noticeably from the full-scale data for the ice thicknesses higher than 0.4 m. A higher value of the friction coefficient with a low value of form drag coefficient (combo-7 in Table 3) indicates very conservative results.

A ‘correct’ value of the form drag and friction coefficients is difficult to measure directly, since both variables depend on a range of conditions, which are often not measured. A friction coefficient of 0.2 is considered reasonable. This value is in line with values that are used in other work. The vertical form drag coefficient of 0.1 is rather low in comparison to the theoretical value of form drag for representative ice rubble shapes. A possible justification of this low value can be found by considering the influence of body interaction on the form drag, which is visualized in Figure 6. During the sliding phase, pressure below the broken ice floes varies with the propulsion speed and its location with respect to hull shape. According to Valanto (2001b), there is a possibility that the mat of broken ice floes lets some water in through the gap between the floes. Hence, the layer is not pressure tight. Therefore, changes in the pressure below the ice flow can influence the pressure in the gaps between the ice floes and may have some effect on the pressure above the ice floes. A thorough analysis is required to investigate this complicated phenomenon. However, the changes in the pressure in the ice floes may result into a decreased form drag force. Along with this, as the broken ice follows the hull geometry, the form drag of the combination of ship hull and broken ice should be considered, rather than the form drag on each individual ice floe in isolation. The effect of the form drag coefficient is very critical for the ice resistance calculations, Combo-4 and Combo-7 from Table 3 have similar friction coefficient (0.25) but variable form drag coefficients (0.3 and 0.1 respectively), and it can be observed from Figure 5 that an increase in form drag results in a more conservative ice resistance prediction.

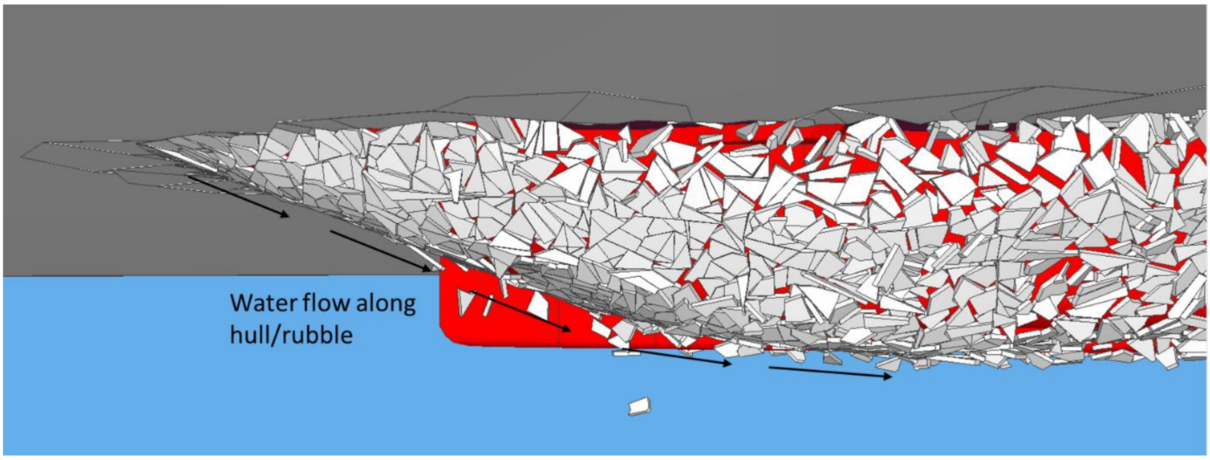

Figure 6: Visualization of ice floes around hull

CONCLUSION

This paper investigates two main aspects; the performance of SAMS in level ice and the sensitivity of the numerical model results to form drag and friction coefficients. The main findings are:

- Performance of SAMS is in level ice is checked by plotting the h-v curve of Oden and comparing it with full-scale data available in the literature. Numerical modelling results and the full-scale measurements are in good agreement, indicating the suitability of using SAMS to simulate ship performance in level ice.
- The simulated h-v curve is sensitive to the used form drag and friction coefficients. The Sensitivity analysis indicates that an out-of-plane form drag coefficient of 0.1 and a friction coefficient of 0.2 results in the best approximation of the measured h-v curve of the icebreaker Oden. The lower value of form drag coefficient indicates that as the broken ice floes follow the hull geometry, the form drag of the combination of sliding ice rubble and ship hull should be considered, instead of form drag on each individual ice floe.

REFERENCES

Akkok, M., Ettles, C.M.M. and Calabrese, S.J., 1987. Parameters affecting the kinetic friction of ice. *Journal of Tribology*, 109(3): 552-561.

Arya, S.P.S., 1975. A drag partition theory for determination the largescale roughness parameter and wind stress on arctic pack ice, *J. Geophys. Res.*, 80, 3447-3454.

Baurle, L., Kaempfer, T., Szabo, D. and Spencer, N., 2007. Sliding friction of polyethylene on snow and ice: Contact area and modeling. *Cold Regions Science and Technology*, 47(3): 276-289.

Berg, M., Lubbad, R. and Løset, S., 2018. An implicit time stepping scheme and improved contact model for an ice structure interaction simulation. *Cold Regions Science and Technology*, 155:193-213.

Daley, C., 1999. Energy based ice collision forces. In: *Proceedings of the 15th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC)*, 2: 672–686.

Enkvist, E., Varsta, P. and Riska, K., 1979. The ship-ice interaction. In: *Proceedings of the 5th International Conference on Port and Ocean Engineering under Arctic Conditions, Trondheim, Norway*, 13-17 August 1979, pp. 977-1002.

Evans, D., Nye, J. and Cheeseman, K., 1976. The kinetic friction of ice. Proceedings of the Royal Society of London, *Series A (Mathematical and Physical Sciences*), 347(1651): 493-512.

Garbrecht, T., Lüpkes, C., Hartmann, J., and Wolff, M. 2002. Atmospheric drag coefficients over sea ice validation of a parameterization concept, *Tellus, Ser. A*, 54, 205–219.

Hanssen, I. and Gjessing, Y., 1988. Observations and model calculations of aerodynamic drag on sea ice in the Fram Strait, *Tellus, Ser. A,* 40, 151–161.

Johansson, B., and Liljestrom, G., 1989, Oden- A state of the art icebreaker. 10th *Intl. Conference, Port and Ocean Engineering under Arctic Conditions*, 12-16 June 1989, Luleaa, Sweden, Proc, v 3, p 1229.

Kämäräinen, J., 2007. *Theoretical investigation on the effect of fluid flow between the hull of a ship and ice floes on ice resistance in level ice.* Ph.D. Helsinki University of Technology.

Keinonen, A., Browne, R., Revill, C. and Reynolds, A., 1996. Icebreaker Characteristics Synthesis. *Report for the Transportation Development Centre, Transport Canada*, Report TP 12812E.

Kotras, T., Baird, A., and Naegle, J., 1983. Predicting ship performance in level ice. *Soc. Nav. Archit. Mar. Eng.* Trans. 95, 329-349.

Lewis, J. and Edward, Y., 1970. Methods for predicting icebreaking and ice resistance characteristics of icebreakers. *SNAME Trans*. 78, 213-249.

Lindqvist G. (1989). A Straightforward Method for Calculation of Ice Resistance of Ships. In: *Proceedings of the 10th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC)*, 722-735.

Lu, P., Li, Z., Cheng, B. and Leppäranta, M., 2011. A parameterization of the ice ocean drag coefficient, *J. Geophys. Res*., *116*, C07019, doi:10.1029/2010JC006878.

Lu, W., Lubbad, R., Høyland, K., Løset, S., 2014. Physical model and theoretical model study of level ice and wide sloping structure interactions. *Cold Regions Science and Technology*. 101, 40–72.

Lu, W., Lubbad, R., Shestov, A., and Løset, S., 2018a. Parallel channels' fracturing mechanism during ice management operations. Part I: theory. *Cold Reg. Sci. Technology*. 156, 102-116.

Lubbad, R. , Løset, S., Lu, W., Tsarau, A., and Berg, M., 2018. An overview of oden arctic technology research cruise 2015 (OATRC2015) and numerical simulations performed with SAMS driven by data collected during the cruise. *Cold Regions Science and Technology*. 156, 1-22. https://doi.org/10.1016/j.coldregions.2018.04.006

Lubbad, R., and Løset, S., 2011. A numerical model for real-time simulation of ship-ice interaction. *Cold Reg. Sci. Technol*. 65 (2), 111–127.

Lüpkes, C., and Birnbaum, G., 2005. Surface drag in the Arctic marginal sea ice zone: A comparison of different parameterization concepts, *Boundary Layer Meteorol.,* 117, 179–211.

Mai, S., Wamser, C., and Kottmaier, C., 1996. Geometric and aerodynamic roughness of sea ice, *Boundary Layer Meteorol.,* 77, 233–248.

Myland, D., and Ehlers,S., 2019. Model scale investigation of aspects influencing the ice resistance of ships sailing ahead in level ice, Ship Technology Research, DOI:10.1080/09377255.2019.1576390

Nguyen, D., Sørbø, A., Sørensen, A., 2009. Modelling and control for dynamic positioned vessels in level ice. In: *Proceedings of 8th Conference of Maneuvering and Control of Marine Craft (MCMC'2009*). 42(18), 229-236.

Puntigliano F. (2003). *Experimental and numerical research on the interaction between ice floes and a ship's hull during icebreaking.* TU Hamburg - Harburg Schriftenreihe Schiffbau, September 2003, Bericht 622.

Riska, K., Wilhelmson, M., Englund, K., and Leiviska, T., 1997. Performance of Merchant Vessels in the Baltic. Research report no 52. *Winter Navigation Research Board*.

Spencer, D., and Jones, S.J., 2001. Model-scale/full-scale correlation in open water and ice for Canadian coast guard "r-class": icebreakers. *J. Ship Res*. 45, 249–261.

Steiner, N., 2001. Introduction of variable drag coefficients into sea ice models, *Ann. Glaciol.*, 33, 181–186.

Su, B., Riska, K., and Moan, T., 2010. A numerical method for the prediction of ship performance in level ice. *Cold Reg. Sci. Technol*. 60, 177–188.

Tan, X., Su, B., Riska, K., and Moan, T., 2013. A six-degrees-of-freedom numerical model for level ice–ship interaction. *Cold Reg. Sci. Technol*. 92, 1–16.

Tsarau, A., Lubbad, R., and Løset, S., 2016. A numerical model for simulating the effect of propeller flow in ice management, *Cold Regions Science and Technology*. doi: 10.1016/j.coldregions.2016.06.002

Valanto, P., 2001. On the Cause and Distribution of Resistance Forces on Ship Hulls moving in Level Ice. *Port and Ocean Engineering under Arctic Conditions, POAC'01*, August 12 - 17, 2001, Ottawa, Ontario, Canada, p. 803 - 813.

Wang, S., 2001. *A Dynamic Model for Breaking Pattern of Level Ice by Conical Structures*, PhD. Department of Mechanical Engineering, Helsinki University of Technology, Finland.