GPU Modeling of Ship Operations in Pack Ice

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ABSTRACT

The paper explores the use of an event-mechanics approach to assess vessel performance in pack ice. The methodology is developed using massively parallel programming strategies on a GPU enabled workstation. A set of simulation domains, each containing hundreds of discrete and interacting ice floes is modeled. A simple vessel is modeled as it navigates through the domains. Each ship-ice collision is modeled, as is every ice-ice contact. Time histories of resistance, speed and position are presented along with the parametric sensitivities. The results are compared to published data from analytical, numerical and scale model tests. The work is part of a large research project at Memorial University called STePS^2 (Sustainable Technology for Polar Ships and Structures).

KEY WORDS: ice forces; pack ice; simulation; GPU, event-mechanics.

INTRODUCTION

The paper presents some preliminary results concerning the use of GPU computer technology to simulate ship-ice interaction. A GPU (Graphics Processing Unit) is a specialized form of computer processor that can be used in the simulation of complex physical phenomena, especially those that benefit from parallel computation. The latest generation of GPUs contains hundreds of parallel processors on a single chip. The (NVidia CUDA) website gives an overview of the technology.

The problem being explored here is the transit of a vessel through open pack ice (see Figure 1), with floes ranging in size from 1m to 20m. A ship transiting this kind of ice cover will not only collide with many floes, but the ice floes will interact in a complex way. A very large number of interactions will occur as a vessel travels even one ship length. The complexity of the problem is more readily handled by using the parallel computing power of a GPU.

The simulation results given here represent only a first step in the use of this technology. The longer term aim of the project is to permit realistic and rapid simulation of a wide range of ship-ice and ice-structure interactions and operations. The simulations presented in this paper, involving simultaneous interactions of hundreds of ice floes have been performed at up to 6x real time.

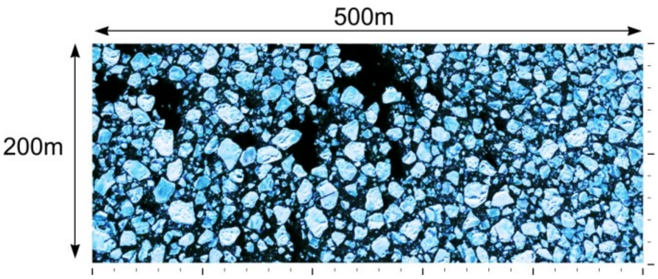

Figure 1. Example of natural first year pack ice

MODEL INPUT

Ice Conditions

The simulations presented below were performed in eight different ice fields. Six of the fields involved randomly shaped and oriented pack ice of varying concentration (see Figure 2 and Figure 3), while two involved regular arrays of equally sized hexagons (see Figure 4) .

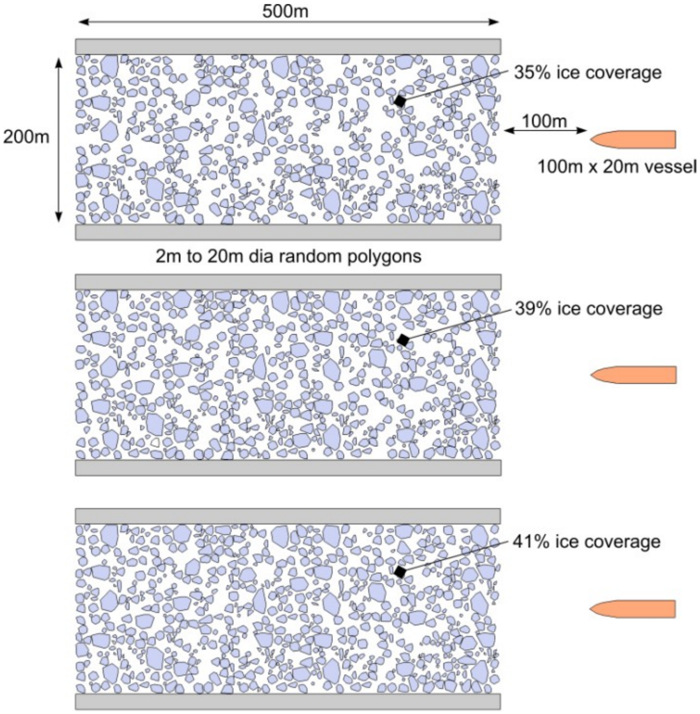

Figure 2. 35%, 39% and 41% simulation domains

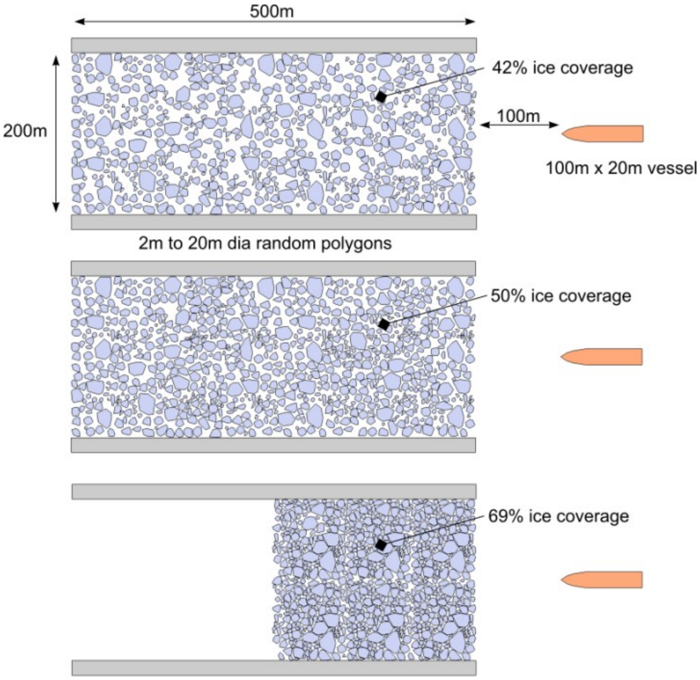

Figure 3. 42%, 50% and 69% simulation domains

Table 1. List of simulation run parameters.

Run #s	Number of Floes	Ice Coverage	Bollard Thrust [kN]	geometry
1.1 to 1.5	560	35%	23, 46, 92,178, 370	random
2.1 to 2.5	581	39%	23, 46, 92,178, 370	random
3.1 to 3.5	618	41%	23, 46, 92,178, 370	random
4.1 to 4.5	657	42%	23, 46, 92,178, 370	random
5.1 to 5.5	456	46%	23, 46, 92,178, 370	hexagonal
6.1 to 6.5	824	50%	23, 46, 92,178, 370	random
7.1 to 7.5	595	60%	23, 46, 92,178, 370	hexagonal
8.1 to 8.5	721*	69%	23, 46, 92,178, 370	random

* in this case there field was 200x 250m instead of the normal 200x500m.

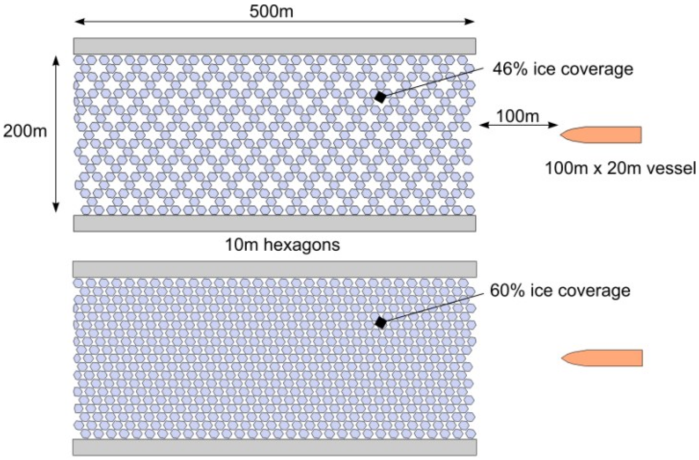

Figure 4. 46% and 60% simulation domains (hexagons)

For the random polygon cases the ice floes were all represented as convex polygons of less than 20 sides. Floes were typically 4 to 7 sided (see Figure 5). The floe characteristic dimensions (defined as the square root of the area) ranged from 2m to 20 m, with a mean of 6.9m and a standard deviation of 3.9m. The floe set was created by drawing polygons on several of the floes in Figure 1 and then making copies of the floes. The different concentrations were created manually by copying floes to increasingly fill in the gaps. For numerical reasons all the simulations started with no floes in contact with any other floes.

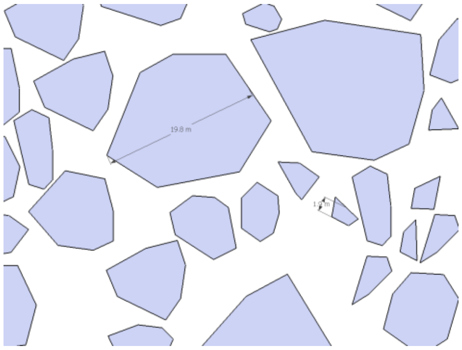

Figure 5. Close-up of Random Polygonal ice floes

For the hexagonal polygon cases, the floes were all the same size, with a characteristic dimension of 10.1m.(see Figure 6) The polygons were slightly rotated, with the intent of breaking the perfect symmetry and diminishing the tendency to interlock.

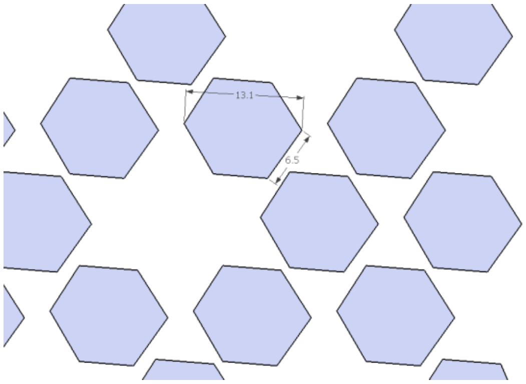

Figure 6. Close-up of hexagonal ice floes

Vessel Description

The vessel used in the simulation has the following nominal properties:

Length: 100m
Beam: 20m
Mass: 7200 tonnes
Geometry: 2D polygon (see Figure 7, 8)

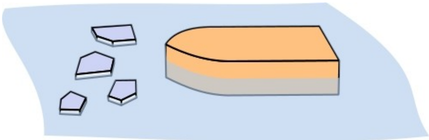

Figure 7. Sketch of 2D concept used in simulations

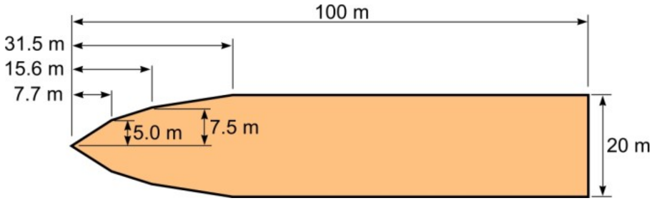

Figure 8. Geometry of vessel polygon

MODEL MECHANICS

Ice Behavior

As stated above, the concept for the simulation is the rapid assessment of a sequence of discrete interactions with a large number of discrete ice objects. The transit of a vessel through pack ice, and the interactions of the ice are modeled as a set of contact events. The movements are treated using simple equations of motion. The individual ice blocks move in the 2D space of the simulation. The position and velocity of each floe is updated every time step. A simple water drag model results in the floes tending to slow. Ice-ice interactions account for both ice crushing impact forces and steady elastic stresses to resist static pressure. In this generation of the model there are no environmental driving forces (wind, current), nor are there any of the more complex responses such as rafting and rubbling. These are being planned for future generations of the model.

Vessel Behavior

The vessel is modeled as only moving forward with a simple self-propulsion algorithm. A simple water resistance model is combined with a simple thrust deduction model to produce a simple net-thrust vs speed effect. In open water, the vessel will accelerate until the net thrust is zero, and then settle at its open water speed. In pack ice the sequence of ice forces will, on average, balance the available net thrust at some speed below the open water speed. In this way the net thrust is a surrogate for time-averaged ice resistance. The process is not steady. Future versions of the model will include more aspects of vessel behavior.

MODEL RESULTS

Field Images

Figure 9 shows an image of a simulation taken as the vessel transits open pack ice. The vessel leave a tack of relatively open water along with a zone where the ice is more closely packed. The ice ahead and to the sides is undisturbed. A very large number is ship-ice and ice-ice contacts have taken place. Figure 10 shows a similar situation, but with 3 images overlaid using partial transparency. This makes it easier to see the ice floe disturbance (termed the "action zone"). The size and shape of the action zone changes as the ice cover becomes more concentrated.

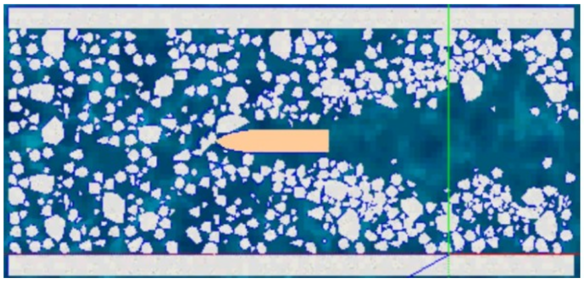

Figure 9. Image from simulation video in 35% coverage

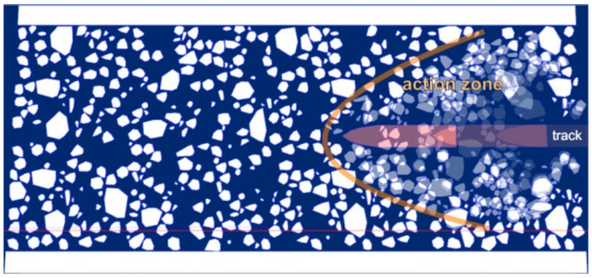

Figure 10. Image from simulation video in 35% coverage showing action zone.

Time Sequence Results

Shown below are three time series plots for the simulation in 35% ice cover with a bollard thrust of 370kN. As the vessel moves through the ice, a sequence on impulses acts on the ship.

The net thrust model tends to keep the ship moving and the vessel tends to settle down to a speed where the ice forces tend to balance the available net thrust. The process is not steady. The ice forces are a series of very short impulses mixed with relatively long periods of no ice loads. Figure 11 shows a portion of the ice impact forces on the vessel. The ice forces are very quick, but do tend to last longer than one simulation step due to the number of floes in contact and the turning (and this re-impact) of the floes. If the entire time history of this data were shown, it appears to be just a sequence of spikes.

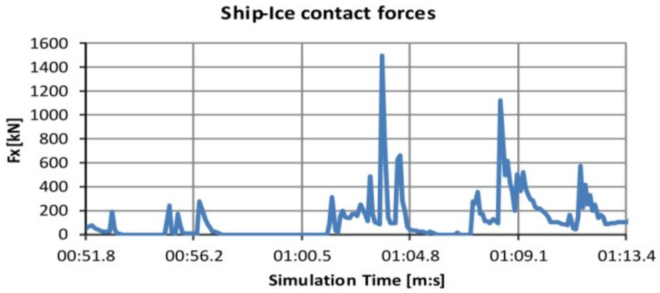

Figure 11. Partial time-history of ice collision forces on the vessel 35% coverage

Figure 12 shows the vessel speed for the entire simulation. At the start, the vessel is set moving at its open water speed. As it enters the ice field it quickly slows to a nearly steady ice speed, though still with fluctuations. The fluctuations are due to the ice impulse loads. Figure 13 shows the net thrust. This time-averaged value of net thrust is effectively the ice resistance, as long as the net acceleration is close to zero.

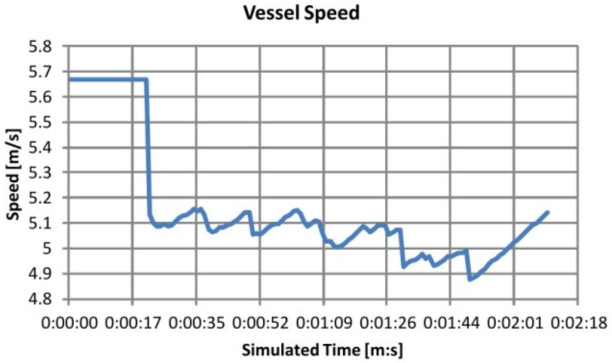

Figure 12. Vessel speed during simulation 35% coverage

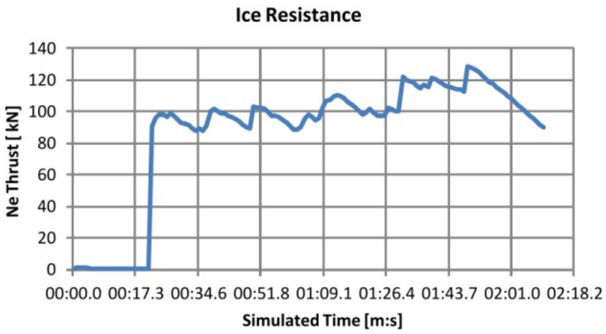

Figure 13. Net Thrust during simulation in 35% coverage

The above plots are representative of the simulations performed. Each impact is tracked. Considerably more data is available for extraction from the simulations, such as the exact location of the impact on the hull. The approach also lends itself to easily including stochastic distributions of ice geometric and strength properties (shape, thickness, strength), which would generate additional data for parametric relationships.

Parametric Results

To illustrate the general validity of the approach as well as to identify areas for improvement, the following section will present parametric trends in the results. The influence of velocity and concentration will be presented and compared to other published data. In the plots below (Figure 14 to Figure 20) the data labeled GPU refers to the present results. WC(2010) refers to an empirical model based on physical model tests (Woolgar and Colbourne, 2010). MA(1989) refers to an analytical model of resistance in pack ice (Muggeridge and Aboulazm 1989).

The ice resistance vs. velocity for various ice concentrations is given in Figure 14 to Figure 18. The plots show two noteworthy aspects. The agreement with MA(1989) is remarkably good, while the agreement with WC(2010) is much less so. This is likely due to several reasons. The MA(1989) model made essentially the same assumptions about contact and energy that are in the GPU simulation. In both cases, all collisions are inelastic, such that energy is absorbed in ice crushing and water drag while momentum is conserved.

The WC(2010) model has a quite different basis. For one thing the WC model is an empirical fit to model test data at higher concentrations. This means that there is some potential for error in the extrapolation to lower concentrations. Secondly and more importantly, the WC physical tests contained a number of physical behaviors that were not part of the GPU model. In the physical model tests the ice was able to flex, raft, and rubble, as well as submerge below a 3D ship shape. These additional behaviors would result in different trend with velocity and concentration. There is also the likelihood that the ice sizes and shapes were different, which may have made a difference. As evidence of this, the GPU simulations in the 60% regular hexagonal pack ice produced resistance resulted in noticeably higher resistance than in random floes. This appeared to be the result of mechanical interlocking amoung the floes.

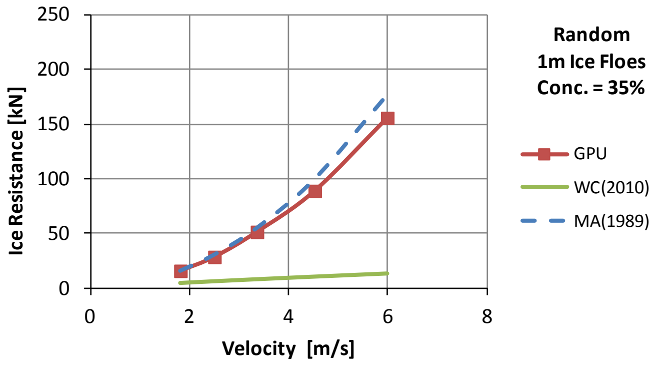

Figure 14. Comparison of Resistance Estimates in 35% coverage

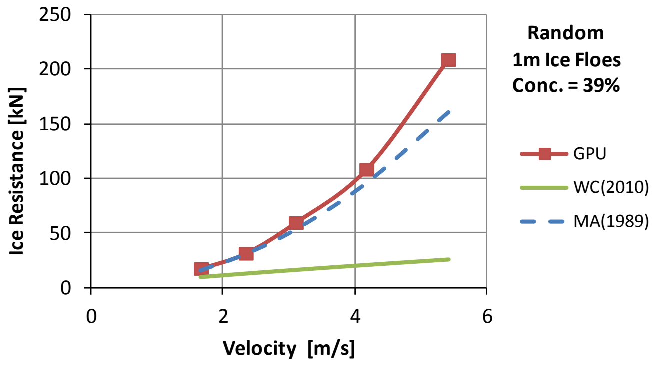

Figure 15. Comparison of Resistance Estimates in 39% coverage

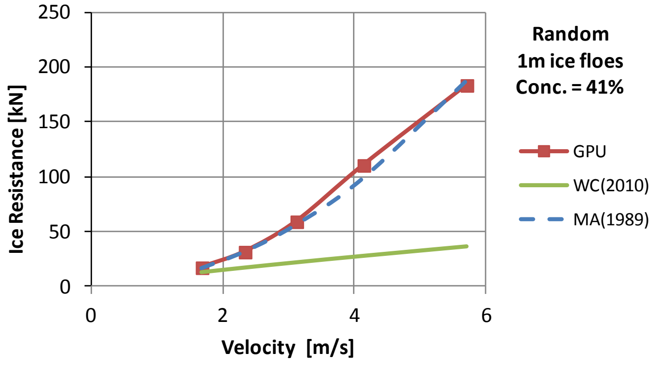

Figure 16. Comparison of Resistance Estimates in 41% coverage

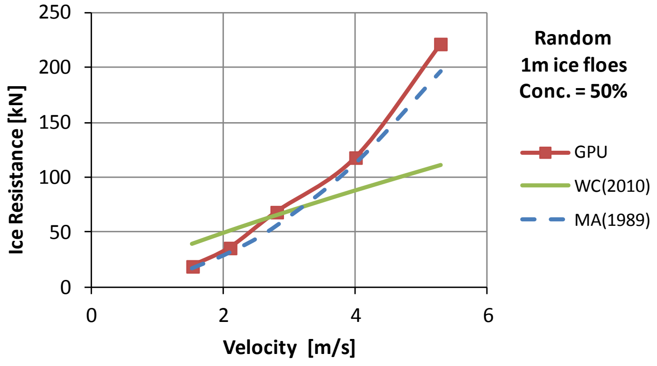

Figure 17. Comparison of Resistance Estimates in 50% coverage

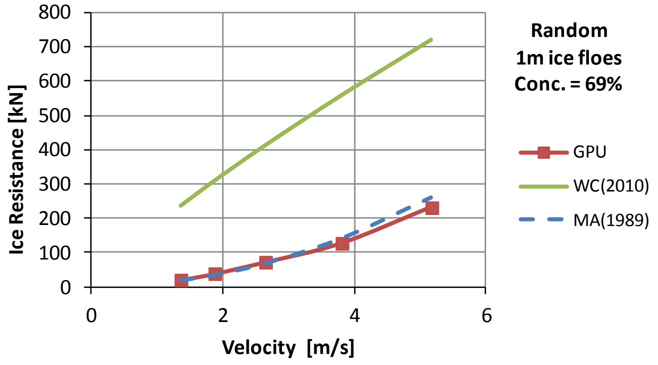

Figure 18. Comparison of Resistance Estimates in 69% coverage

Figure 19 shows the trends of resistance vs. velocity for all the concentrations with random floes. The curves are approximately quadratic (i.e. exponent on velocity is close to two).

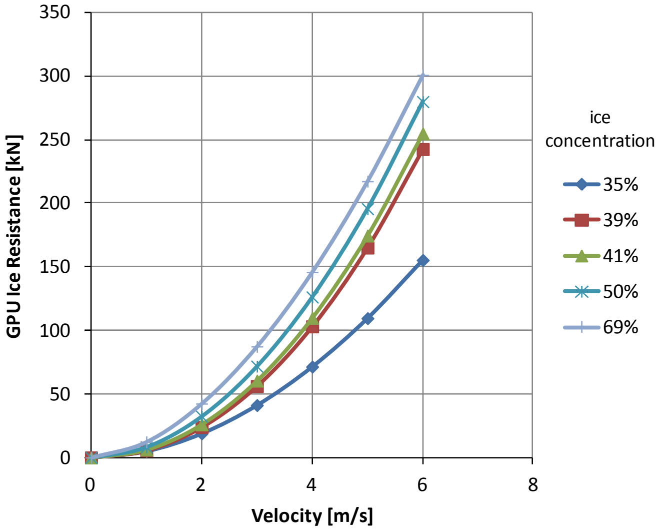

Figure 19. GPU model Resistance Estimates vs. velocity

Figure 20 shows the trends vs. ice concentration. One interesting aspect to note is that the relationship is close to linear at slower speeds and becomes much less so at higher speed. This could be the result of the change in the size of the action zone as speed increases.

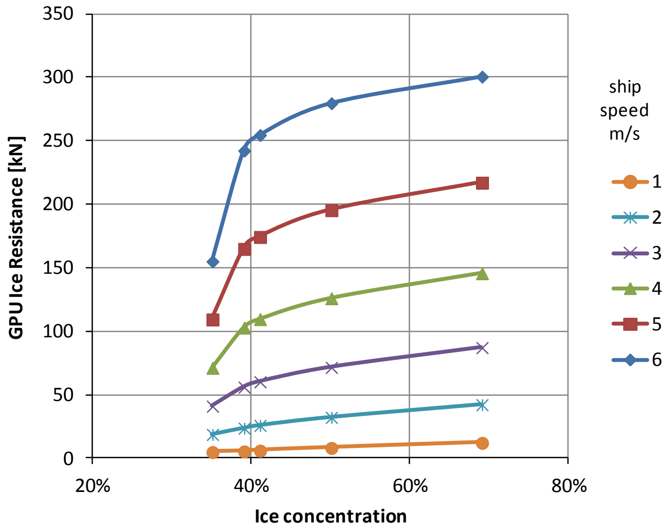

Figure 20. GPU model Resistance Estimates vs. concentration.

CONCLUSIONS AND RECOMMENDATIONS

The simulation results presented above show the potential for use of GPU simulation of problems in ice mechanics. The open pack resistance results are interesting, though generally similar to expected results. More interesting is the potential for this form of modeling. The model focuses on the event sequence rather than on the continuum mechanics of a single event. Each event forms a step in the development of the results and creates the initial conditions for the next event. The event sequence is a nonlinear process and does not lend itself to easy analytical description. The GPU computation methodology enables the solution of a relatively long and realistic chain of events. Current results are being achieved at speeds faster than real time with the probability that significant increases in speed are yet achievable.

As ships operate in pack ice, a complex set of events takes place. The navigation strategies used by the operator result in many impacts all around the vessel. While some of these interactions are relatively easy to understand and predict, others are not. One question for instance is the likely lateral impact speeds on the midbody while operating in pack ice, with consideration of thickness and ice shape. It is likely that years of experience would enable operators to avoid certain maneuvers that would expose the midbody to overloads. Field studies of such details would potentially also require years of trials, something that is not generally affordable. Real-time training and hyper-real-time modeling using the power of GPU simulation should enable the study of ice loads during realistic operations in complex natural ice. Naturally such studies would best be supported and validated by field trials and other modeling approaches.

GPU simulations offer a new approach for tackling some important current arctic shipping and engineering challenges, including the development of safe speed recommendations for polar class hips and developing ice management strategies for arctic offshore structural design and support.

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