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GPU-Event-Mechanics Evaluation of Ice Impact Load Statistics

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Abstract

The paper explores the use of a GPU-Event-Mechanics (GEM) simulation to assess local ice loads on a vessel operating in pack ice. The methodology uses an event mechanics concept implemented using massively parallel programming on a GPU enabled workstation. The simulation domain contains hundreds of discrete and interacting ice floes. A simple vessel is modeled as it navigates through the domain. Each ship-ice collision is modeled, as is every ice-ice contact. Each ship-ice collision event is logged, along with all relevant ice and ship data. Thousands of collisions are logged as the vessel transits many tens of kilometers of ice pack. The GEM methodology allows the simulations to be performed much faster than real time. The resulting impact load statistics are qualitatively evaluated and compared to published field data. The analysis provides insight into the nature of loads in pack ice. The work is part of a large research project at Memorial University called STePS2 (Sustainable Technology for Polar Ships and Structures).

Introduction

Ice class vessels are unique in a number of ways in comparison to non-ice class vessels. Hull strength, power, hull form and winterization aspects are all issues that raise special challenges in the design of ice class ships. This paper focuses on matters of local ice loads which pertain to hull strength in ice class vessels. More specifically, the paper examines the parametric causes of local ice loads and statistics that result as a ship transits through open pack ice.

The issue of pack ice transit is of interest to those wishing to operate safely in such conditions. One key question is that of safe operational speeds. Consider the special case of open pack ice, where floes are relatively small, numerous and resting in calm water. A vessel moving through such an ice cover would experience a series of discrete collisions. As long as a vessel moved very slowly, the loads would be very low. In such a case the vessel could make safe and steady progress, even if it had a relatively low ice class. However, if the vessel attempted to operate more aggressively, impact speeds would increase and a higher ice class would be needed for safe operations. The investigation below provides some insight into the factors that influence the loads in this situation. These factors include hull form, speed, floe size and concentration, ice thickness, strength and edge shape. Most prior studies have tended to focus on ice thickness and strength as the primary determinants of load. This study shows that ice edge shape and mass, along with hull form and locations are also strong determinants of loads, and especially the load statistics. The simulations provide some interesting data, especially when compared to field trials data.

A related focus for the study is to explore the use of the GPU-Event-Mechanics (GEM) simulation approach. The GEM approach represents the integration of a number of concepts. The physical space is described as a set of bodies. The movement (kinematics) of the bodies is tracked using simple equations of motion. Time is divided into relatively long ‘moments’, during which events occur. All variables in the simulation; forces, movements, fractures and other changes, are considered to be aspects of events. Some events are momentary, while others are continuing. Some events involve a single body and are termed solo events. Motion, for example, is treated as a solo event. Some events are two-body events. Impact is an example of a two-body event. The GEM approach lends itself to parallel implementation, which in this case is accomplished in a GPU environment. A GPU (Graphics Processing Unit) is a common element found in modern computer graphics cards. The GPU is primarily intended for making rapid calculations associated with the display. However, special software can access the GPU and enhance the computing power available to the user. See (Daley et.al. 2012) for further discussion of GPUs.

The event models are the analytical solutions of specific scenarios. As a result, the events do not require solution (in the numerical sense) during the GEM simulation. The event solution is merely invoked for the specific inputs that arise at that point in the GEM simulation. For example, the collision load depends on the specific shape and position of the ice floe, as well as thickness, flexural strength and crushing behavior. The load also depends on hull form and impact location, as well as the mass properties of the ship. There are dozens of input variables which influence the specific event parameters. Nevertheless, the computation problem is far smaller than if the continuum mechanics were to be solved for each collision event. The GEM model focuses on the large scale system involving a large number of bodies, rather than on any single impact. The GEM model is able to compute complex simulation results at rates faster than real time. This feature has great practical significance for design, assessment and training applications.

Simulation Approach

Figure 1 shows an example of the type of ice cover that will be examined in the GEM simulations. An earlier paper (Daley et.al. 2012) presented some initial results for vessel operations in this type of ice cover. The focus of (Daley et.al. 2012) was on ship resistance, which is the time-averaged net ice force acting along the long axis of the vessel, integrated over the whole vessel. Such values are of interest for powering and performance calculations. Figure 2 shows one of several simulation cases examined. Figure 3 shows a close-up of the 2D polygonal ice floes that are used to represent the ice cover. The polygons were developed by digitizing a part of the image in Figure 1 and replicating the polygons to fill the simulation space. In (Daley et.al. 2012) all the ice floes were of the same thickness.

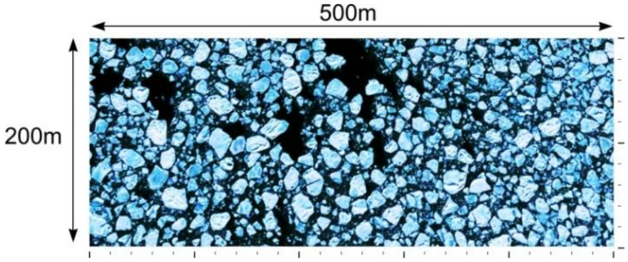


Figure 1. Example image of natural first year pack ice

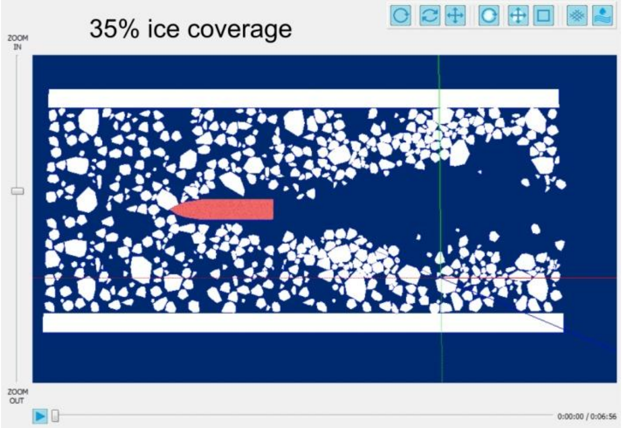


Figure 2. Simulation domain with 35% ice cover.

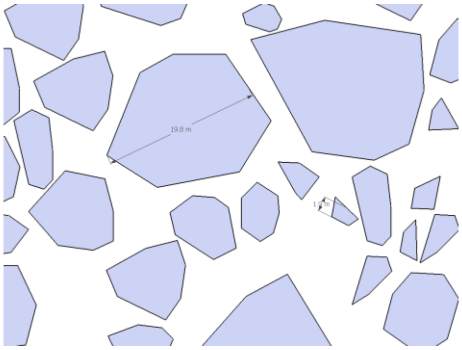


Figure 3. Close-up of Random Polygonal ice floes

The focus of the present paper is on local structural loads. As the vessel transits through the ice pack, a series of collisions occur. The emphasis in this presentation is to give only an overview of the mechanics and simulation approach used in the model, hopefully sufficient to give the reader a good idea of the kind of assumptions and features of the software. The details of the equations and software coding would require a much longer presentation. The focus here is to present a number of model results and discuss the value of the approach presented.

Each ice-ice collision event within the pack is treated using a method that can be traced to Popov et. al (1967). The method was updated to reflect pressure-area effects (Daley, 1999), and used for a variety of ship-ice interaction scenarios (Daley and Kendrick 2008). When two bodies collide in a 2D world, each body has 3 degrees of freedom, as well as two mass parameters, and a shape (see Figure 4). The large number of parameters makes the collision problem potentially very difficult. The problem can be substantially simplified by making a few simplifying assumptions and viewing the problem from the perspective of the collision point. It is assumed that the collision will be of short duration, and that the force will act, in the frictionless case, normal to the line of contact (see Figure 5). With these assumptions the problem can be reduced to an equivalent one dimensional collision. The equivalent velocity is the closing velocity at the point of contact along the collision normal.

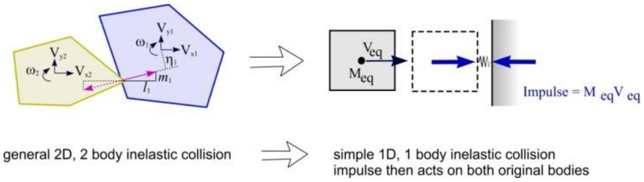
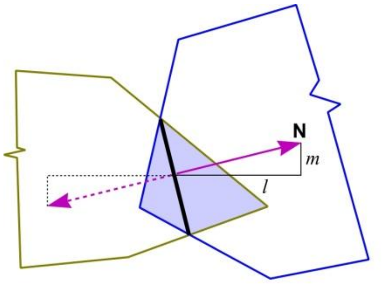


Figure 4. Idealization of 2D collision between two finite bodies.



Contact Force is assumed to be Normal to 'line' of contact defined by overlap region. Force acts from center of line.

Figure 5. Assumption concerning the location and direction of impact forces.

The mass reduction factor (R) for one body subject to a collision along a normal is;

$$R = l^2 + m^2 + \frac{\eta^2}{r_x^2}$$

Where l and m are direction cosines of the inward normal vector, η is the moment arm of the normal vector about the centroid and r_x^2 is the square of the radius of gyration of the body (see Figure 4). Each body in a two body collision has a unique mass reduction factor. The above mass reduction factor represents the simplest case for 2D without added mass or friction. Enhancements to the formula have been developed to include effects of hydrodynamic added mass and friction and 3D effects (see Daley 1999).

The program assumes that all collisions are inelastic, where the ice crushing energy absorbs all the effective kinetic energy. A collision is detected in one time step when the two bodies are found to overlap. The effective masses and normal velocities are determined for each colliding body for their respective points of impact. The direction of relative motion is determined to allow the determination of the friction direction. The impulse that will eliminate the net normal velocity is then found. That impulse is applied to each body in an equal and opposite sense. The result is that the normal velocity at that point is zero in the next time step. This does not mean that all motion is stopped. Ice floes tend to rotate around the collision point and slide away. This approach does contain some idealizations and approximations, but does appear to be stable and produce reasonable results.

As the focus of this paper is structural loads, the actual impact forces are also required. The forces are found by using the "process pressure-area" relationship for ice, the ice edge shape, hull angles, and effective mass of each collision (see Daley 1999). It should be noted that two distinct versions of this approach are used in the GEM simulation. The kinematics of the vessel and ice are modeled in 2D, so one implementation of the model derives the 2D forces. Those algorithms assume that the vessel is wall sided, and do not permit ice to move under the hull. Another algorithm takes the hull form into account and determines impact forces using the 3D mechanics and shapes. These 3D forces are logged for later analysis. For the above reasons, the simulation presented is termed a 2.5D simulation. It is for this reason that the simulations are limited to open pack. High ice concentrations and pressure in the ice pack would create conditions that would invalidate the assumptions. Future model development is planned to remove these restrictions.

Vessel Description

The vessel currently simulated is 100m long and 20 m wide. The vessel is meant to represent a large offshore supply vessel with some ice capability. In plan view, the vessel's waterline is a polygon as shown in Figure 6. The bow of the vessel is sloped as an ice-going vessel would be. Figure 7 shows the 3D shape of the vessel.

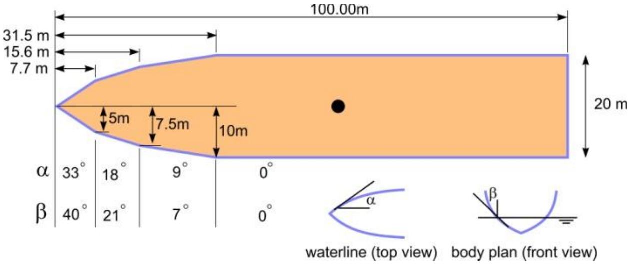


Figure 6. Geometry of 2D vessel polygon with 3D hull angles.

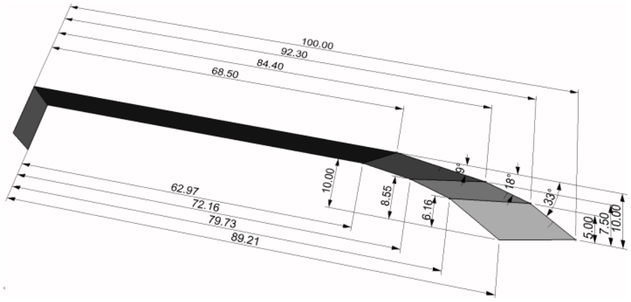


Figure 7. 3D shape of the vessel (half hull shown).

The vessel moves through the ice pack using a simple auto pilot model, rather than at a fixed speed and direction. There is a constant-power thrust and water resistance model which combines the effects of a reduction in net vessel resistance and an increase in propeller thrust as the vessel is slowed. In the absence of the pack ice, this net thrust model brings the vessel to a steady forward speed from a standing or moving start.

$$T_{net} = T_{bollard} - C_{resistance} V^3$$

Where:
T_{net} is the net thrust applied to the vessel model
$T_{bollard}$ is an arbitrary assigned bollard (zero speed) thrust
V is the ship velocity

The constant $C_{resistance}$ incorporates both resistance reduction and thrust increase effects and is calculated for each bollard thrust such that the net thrust is zero at a given open water speed V_{OW}. This model means that the vessel has a declining net force applied to it as the speed increases and will find a lower equilibrium speed as the average ice force from ice impacts increases. The simulations cover 5 power levels, which are expressed in terms of the bollard thrust from a low of 46.25kN to a high of 740kN of thrust.

When the vessel strikes an ice floe it can be slowed or deflected or both. Course control is achieved by providing un-coupled heading and sway Proportional-Derivative controls that apply a countering sway force and a countering yaw moment when deviations in the set heading and course line are detected. Damping is provided by sway and yaw velocity dependent terms.

In Yaw:

$$M_{yaw} = G_1 \delta\theta + G_2 \frac{d\theta}{dt}$$

and in Sway:

$$F_{sway} = G_3 \delta y + G_4 \frac{dy}{dt}$$

Where:
M_{yaw} is the correcting moment
$\delta\theta$ is the deviation from the set heading
F_{sway} is the correcting sway force
δy is the deviation from the set track
G_1,G_2,G_3,G_4 are controller gains that are set to achieve the desired course holding characteristics

This simple autopilot steers the vessel back on course. In this way the vessel more realistically responds to the multiple collisions that it experiences. Floe impacts tend to slow the vessel and cause deviations in the track and heading but these deviations are countered by the change in thrust or changes in moment and sway force.

Impact Algorithm Check

The collision model used in the GEM simulation has a relatively simple analytical solution that can be solved in a spreadsheet. To check that the GEM software is producing the expected impact results for a variety of cases, a set of 32 calibration impacts were modeled in both the GEM program and a spreadsheet. In each of the 32 cases a 10m x 10m ice floe was placed directly in front of the vessel and allowed to strike. The GEM forces were compared to the spreadsheet results. The comparison is shown in Figure 8. There were some small differences attributed to the slight differences in the contact locations that arise in the numerical model. Overall the agreement is excellent and confirms that no gross errors occurred in the implementation.

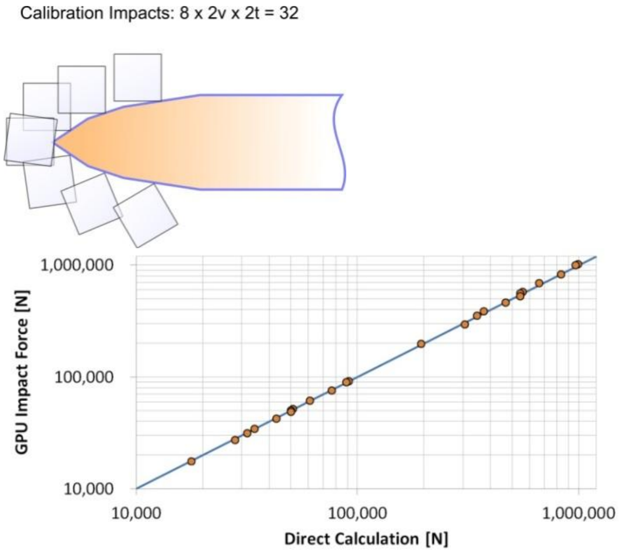


Figure 8. Direct vs. GEM impacts compared for validation purposes.

Simulation Description

The simulations presented all involve a ship transiting through a 200m x 500m pack ice region at a set power level. One example case is shown in Figure 9. The ice represents 4/10th ice cover, with a mix of thin, medium and thick first year ice (0.5m, 0.7m and 1.2m floes). The floes are random in size (same range for each thickness). The egg code that represents the ice is shown. Table 1 describes the 70 individual runs that form the data for this paper. A summary of the key simulation parameters and results are given. The ice floes are comprised of 3 groups of random polygons. Each group can be assigned a common thickness and in this way a wide variety of cases can be developed depending on which thickness values are assigned to which ice group. Two of the groups represents 1/10th coverage (10% of the surface area) while one group represents 2/10th coverage. In total there are 668 unique ice floes, which are combined in various ways and assigned various thicknesses in the various runs.

In total, in the 70 runs performed there were 28,685 ship-ice collisions recorded, which are the basis of the analysis presented. It should be noted that many more ice-ice and ice-wall collisions were simulated but were not logged, nor were the ice resistance values. The GEM approach lends itself to a variety of potential uses.

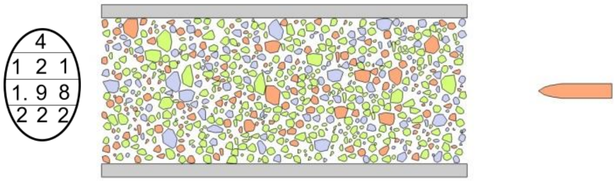
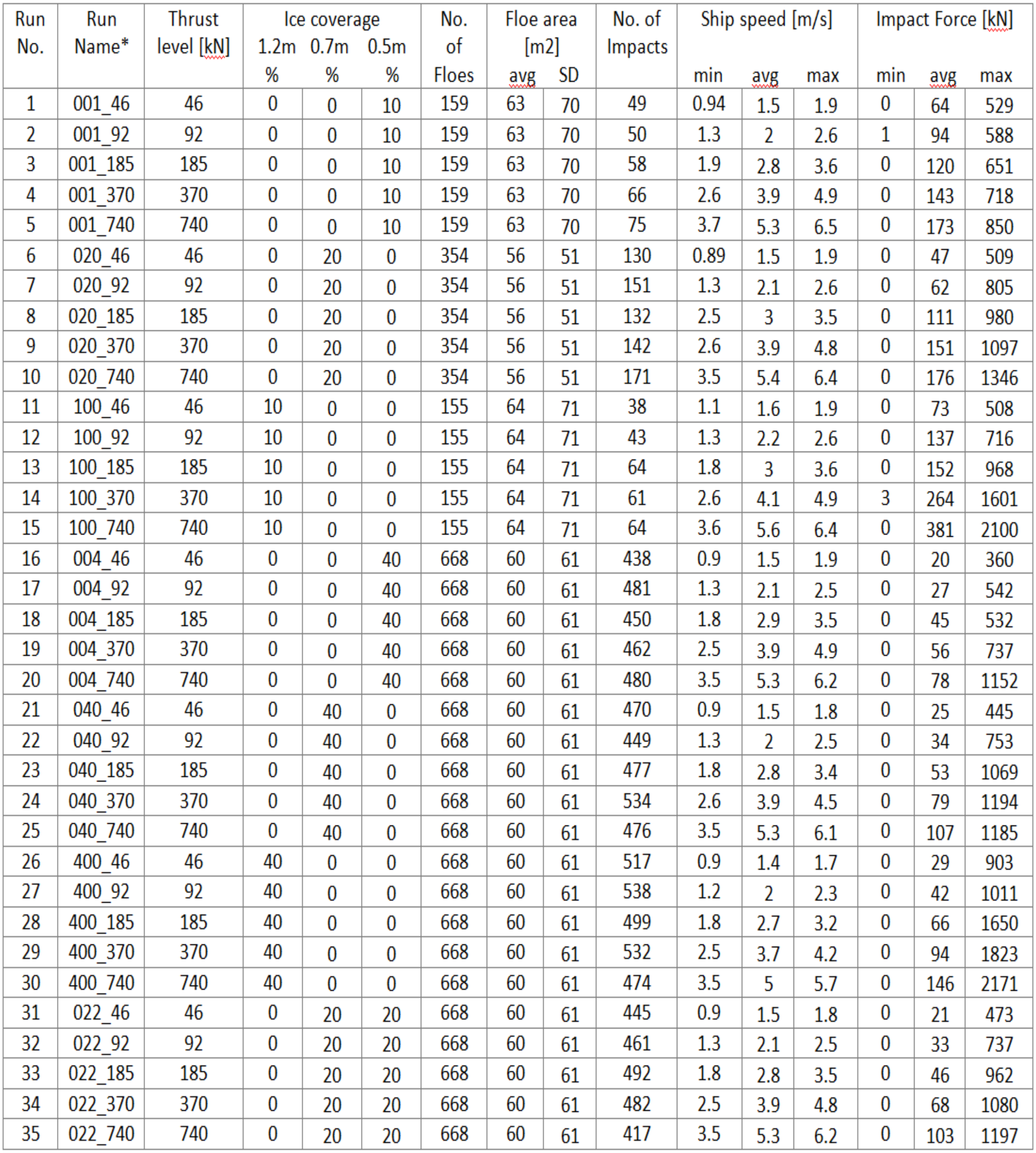


Figure 9. Ice Conditions for Runs 46 through 50.

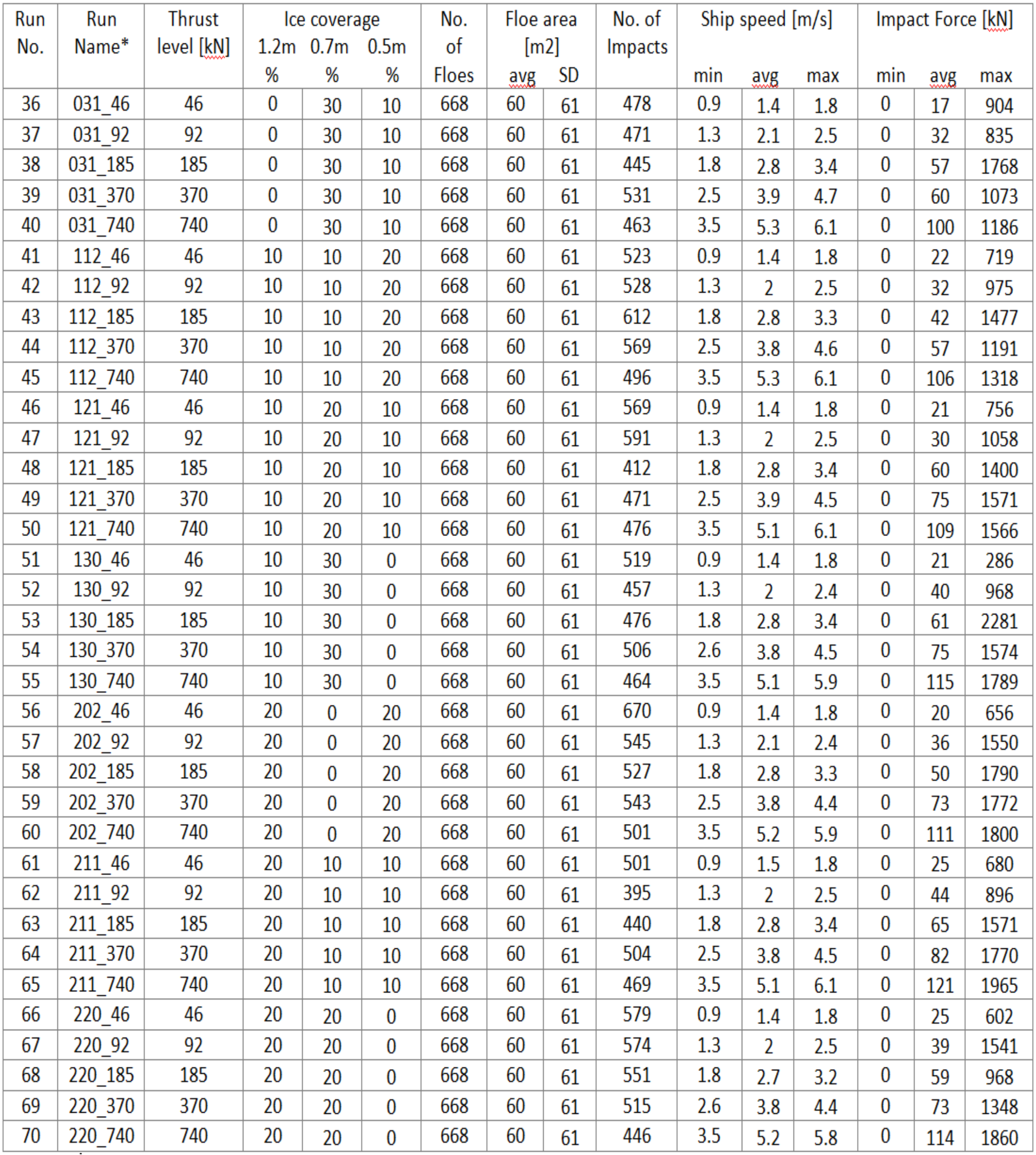
Table 1 Listing of first 35 run cases, with summary result values.



Run No.	Run Name*	Thrust level [kN]	Ice coverage 1.2m %	0.7m %	0.5m %	No. of Floes	Floe area [m2] avg	SD	No. of Impacts	Ship speed [m/s] min	avg	max	Impact Force [kN] min	avg	max
1	001_46	46	0	0	10	159	63	70	49	0.94	1.5	1.9	0	64	529
2	001_92	92	0	0	10	159	63	70	50	1.3	2	2.6	1	94	588
3	001_185	185	0	0	10	159	63	70	58	1.9	2.8	3.6	0	120	651
4	001_370	370	0	0	10	159	63	70	66	2.6	3.9	4.9	0	143	718
5	001_740	740	0	0	10	159	63	70	75	3.7	5.3	6.5	0	173	850
6	020_46	46	0	20	0	354	56	51	130	0.89	1.5	1.9	0	47	509
7	020_92	92	0	20	0	354	56	51	151	1.3	2.1	2.6	0	62	805
8	020_185	185	0	20	0	354	56	51	132	2.5	3	3.5	0	111	980
9	020_370	370	0	20	0	354	56	51	142	2.6	3.9	4.8	0	151	1097
10	020_740	740	0	20	0	354	56	51	171	3.5	5.4	6.4	0	176	1346
11	100_46	46	10	0	0	155	64	71	38	1.1	1.6	1.9	0	73	508
12	100_92	92	10	0	0	155	64	71	43	1.3	2.2	2.6	0	137	716
13	100_185	185	10	0	0	155	64	71	64	1.8	3	3.6	0	152	968
14	100_370	370	10	0	0	155	64	71	61	2.6	4.1	4.9	3	264	1601
15	100_740	740	10	0	0	155	64	71	64	3.6	5.6	6.4	0	381	2100
16	004_46	46	0	0	40	668	60	61	438	0.9	1.5	1.9	0	20	360
17	004_92	92	0	0	40	668	60	61	481	1.3	2.1	2.5	0	27	542
18	004_185	185	0	0	40	668	60	61	450	1.8	2.9	3.5	0	45	532
19	004_370	370	0	0	40	668	60	61	462	2.5	3.9	4.9	0	56	737
20	004_740	740	0	0	40	668	60	61	480	3.5	5.3	6.2	0	78	1152
21	040_46	46	0	40	0	668	60	61	470	0.9	1.5	1.8	0	25	445
22	040_92	92	0	40	0	668	60	61	449	1.3	2	2.5	0	34	753
23	040_185	185	0	40	0	668	60	61	477	1.8	2.8	3.4	0	53	1069
24	040_370	370	0	40	0	668	60	61	534	2.6	3.9	4.5	0	79	1194
25	040_740	740	0	40	0	668	60	61	476	3.5	5.3	6.1	0	107	1185
26	400_46	46	40	0	0	668	60	61	517	0.9	1.4	1.7	0	29	903
27	400_92	92	40	0	0	668	60	61	538	1.2	2	2.3	0	42	1011
28	400_185	185	40	0	0	668	60	61	499	1.8	2.7	3.2	0	66	1650
29	400_370	370	40	0	0	668	60	61	532	2.5	3.7	4.2	0	94	1823
30	400_740	740	40	0	0	668	60	61	474	3.5	5	5.7	0	146	2171
31	022_46	46	0	20	20	668	60	61	445	0.9	1.5	1.8	0	21	473
32	022_92	92	0	20	20	668	60	61	461	1.3	2.1	2.5	0	33	737
33	022_185	185	0	20	20	668	60	61	492	1.8	2.8	3.5	0	46	962
34	022_370	370	0	20	20	668	60	61	482	2.5	3.9	4.8	0	68	1080
35	022_740	740	0	20	20	668	60	61	417	3.5	5.3	6.2	0	103	1197

*Each run name is of the form: nnn_p. The first 3 'n's refer to the coverages in 10ths of the 3 different thicknesses. The p number is the thrust level in KN. All runs were a transit of a 500 m long ice field (x 200 m wide).
** min, mean and max values

Table 2 Listing of last 35 run cases, with summary result values.



Run No.	Run Name*	Thrust level [kN]	Ice coverage 1.2m %	0.7m %	0.5m %	No. of Floes	Floe area [m2] avg	SD	No. of Impacts	Ship speed [m/s] min	avg	max	Impact Force [kN] min	avg	max
36	031_46	46	0	30	10	668	60	61	478	0.9	1.4	1.8	0	17	904
37	031_92	92	0	30	10	668	60	61	471	1.3	2.1	2.5	0	32	835
38	031_185	185	0	30	10	668	60	61	445	1.8	2.8	3.4	0	57	1768
39	031_370	370	0	30	10	668	60	61	531	2.5	3.9	4.7	0	60	1073
40	031_740	740	0	30	10	668	60	61	463	3.5	5.3	6.1	0	100	1186
41	112_46	46	10	10	20	668	60	61	523	0.9	1.4	1.8	0	22	719
42	112_92	92	10	10	20	668	60	61	528	1.3	2	2.5	0	32	975
43	112_185	185	10	10	20	668	60	61	612	1.8	2.8	3.3	0	42	1477
44	112_370	370	10	10	20	668	60	61	569	2.5	3.8	4.6	0	57	1191
45	112_740	740	10	10	20	668	60	61	496	3.5	5.3	6.1	0	106	1318
46	121_46	46	10	20	10	668	60	61	569	0.9	1.4	1.8	0	21	756
47	121_92	92	10	20	10	668	60	61	591	1.3	2	2.5	0	30	1058
48	121_185	185	10	20	10	668	60	61	412	1.8	2.8	3.4	0	60	1400
49	121_370	370	10	20	10	668	60	61	471	2.5	3.9	4.5	0	75	1571
50	121_740	740	10	20	10	668	60	61	476	3.5	5.1	6.1	0	109	1566
51	130_46	46	10	30	0	668	60	61	519	0.9	1.4	1.8	0	21	286
52	130_92	92	10	30	0	668	60	61	457	1.3	2	2.4	0	40	968
53	130_185	185	10	30	0	668	60	61	476	1.8	2.8	3.4	0	61	2281
54	130_370	370	10	30	0	668	60	61	506	2.6	3.8	4.5	0	75	1574
55	130_740	740	10	30	0	668	60	61	464	3.5	5.1	5.9	0	115	1789
56	202_46	46	20	0	20	668	60	61	670	0.9	1.4	1.8	0	20	656
57	202_92	92	20	0	20	668	60	61	545	1.3	2.1	2.4	0	36	1550
58	202_185	185	20	0	20	668	60	61	527	1.8	2.8	3.3	0	50	1790
59	202_370	370	20	0	20	668	60	61	543	2.5	3.8	4.4	0	73	1772
60	202_740	740	20	0	20	668	60	61	501	3.5	5.2	5.9	0	111	1800
61	211_46	46	20	10	10	668	60	61	501	0.9	1.5	1.8	0	25	680
62	211_92	92	20	10	10	668	60	61	395	1.3	2	2.5	0	44	896
63	211_185	185	20	10	10	668	60	61	440	1.8	2.8	3.4	0	65	1571
64	211_370	370	20	10	10	668	60	61	504	2.5	3.8	4.5	0	82	1770
65	211_740	740	20	10	10	668	60	61	469	3.5	5.1	6.1	0	121	1965
66	220_46	46	20	20	0	668	60	61	579	0.9	1.4	1.8	0	25	602
67	220_92	92	20	20	0	668	60	61	574	1.3	2	2.5	0	39	1541
68	220_185	185	20	20	0	668	60	61	551	1.8	2.7	3.2	0	59	968
69	220_370	370	20	20	0	668	60	61	515	2.6	3.8	4.4	0	73	1348
70	220_740	740	20	20	0	668	60	61	446	3.5	5.2	5.8	0	114	1860

*Each run name is of the form: nnn_p. The first 3 ‘n’s refer to the coverages in 10ths of the 3 different thicknesses. The p number is the thrust level in KN. All runs were a transit of a 500 m long ice field (x 200 m wide).
** min, mean and max values

The ice floes are represented as convex polygons with a range of apex angles. The angles for all 668 floes were analyzed to examine the distribution of the values. As shown in Figure 10, the angles appear to follow a Weibull distribution, though not perfectly. One interesting aspect is that the angles are limited to 180 degrees. The Weibull distribution appears to fit the data quite well, but fails to capture the fixed upper limit at 180. As can be seen from Figure 10, the Weibull model would predict that a small number of apex values would be above 180 degrees.

While this is obviously impossible (for convex shapes), the model appears to fit the bulk of the data quite well. This statistical modeling was performed using the Minitab software (Minitab 2013). The reason for presenting these values is that the floe apex angle is one of the key input parameters that determines the impact force values. The higher apex angles result in higher force values. This relationship may be counter-intuitive. The reason is that higher angles mean a more rapid rise in area and force as contact occurs, resulting in a 'harder' impact.

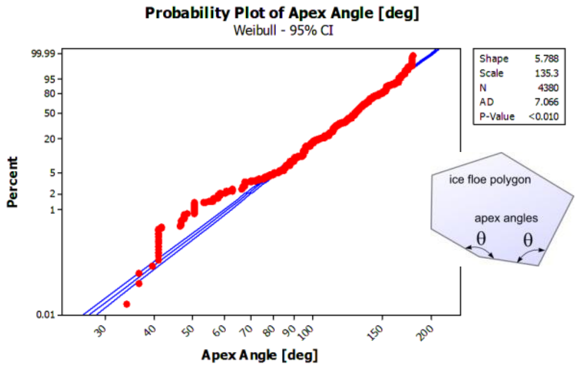


Figure 10. Probability plot for ice floe apex angle data.

Another important input parameter is the ice floe mass. Figure 11 shows the mass statistics for all 668 floes and also for the set of 2520 impacted floes that occurred in runs 46-50. The floe mass is determined by the product of area, thickness and mass density. The mass values appear to follow a lognormal distribution. It appears that the floes impacted are representative of the whole population. This would be expected in the case of the simple navigation strategy modeled here. If a more sophisticated hazard avoidance strategy were to be modeled one might expect a different result. The distributions of apex angle and floe mass are the result of the shapes and sizes of the ice floes in the digitized image (Figure 1), rather than being user determined.

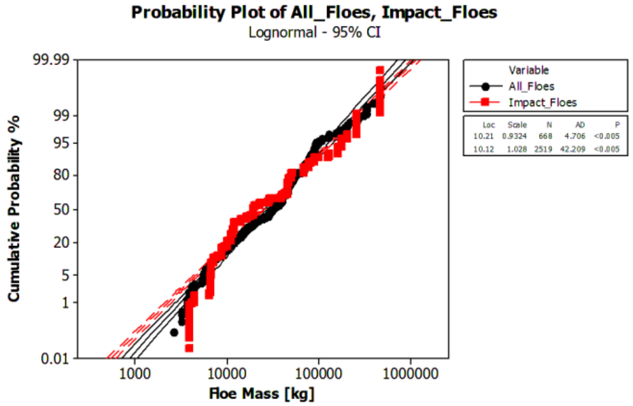


Figure 11. Probability plot for ice floe mass values, for both all floes and just those floes struck in runs 46-50.

Parametric Results

There are various kinds of parametric simulation results that will be presented below. These particular results are from runs 46-50, which involve 10% thick ice, 20% medium ice and 10% thin ice. The five runs are for a range of power levels and velocities, and cover 2.5km of transit.

Figure 12 shows the set of locations of the impacts on the bow. The points tend to be on the hull edge, though there are cases where contact could appear to be inside or outside the hull. This is because of the way contact is defined, as is sketched in the figure. There tends to be a greater number of impacts towards the stem. Figure 13 quantifies this trend by plotting the percentage of impacts that occur within each meter of width of the vessel. In a simple estimate of the rate of impacts per meter width, one might expect that the rate per meter would be constant. This is because each meter will sweep through the same area of ice cover and nominally sweep over the same number of floes (assuming a uniform ice cover as in this case). However, the actual kinematics of the collisions tend to result in the more forward collisions creating a shadow or shield that lowers the number of collisions further aft. This trend might change significantly if more complex navigation practices were to be modeled. The navigation here was just a simple auto pilot with no attempt to avoid any specific features.

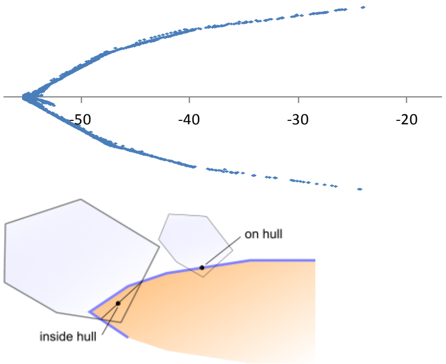


Figure 12. Plot of impact locations on the vessel (runs 46-50).

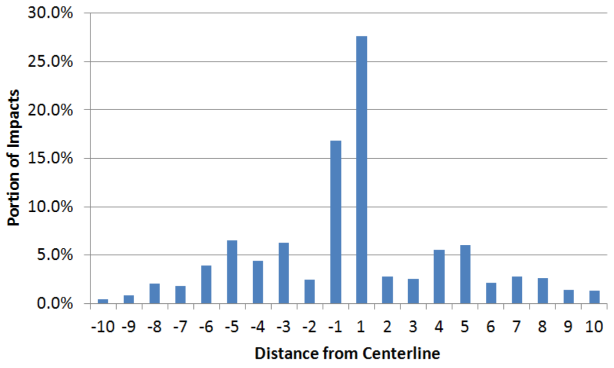


Figure 13. Plot of % impacts vs. lateral distance from centerline. (runs 46-50).

Figure 14 plots the magnitude of the impact forces vs. the distance from the stem. This shows the maximum forces occur closer to the stem. The specific shape of the vessel (waterline and frame angles) will influence these results, possibly strongly. In this paper only one hull form has been examined.

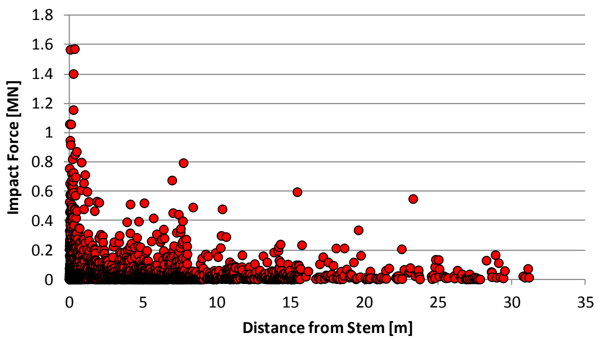


Figure 14. Plot of impacts forces vs. distance aft from stem. (runs 46-50).

Figure 15 plots the magnitude of the impact forces vs. the vessel speed. The data has the typical appearance of field data (see Figure 20) where trends are easily obscured by the mass of variable data. The variations are also influenced by hull shape, floe size, thickness and apex angle. The effect of velocity can be obscured. A trend line through the data is most strongly influenced by the majority of small impacts. The equation relating mean force to velocity is;

$$F = .0023\ v^{1.68}\quad [MN]$$

The higher values of force appear to be following a somewhat different trend, in that they appear to be limited to a force of 1.6 MN. This is obviously an artifact of the specific simulation rather than an actual limit. The load mechanics used in the simulation are deterministic and as such the forces should be bounded. In most impacts the various input parameters combine to produce load lower than the maximum.

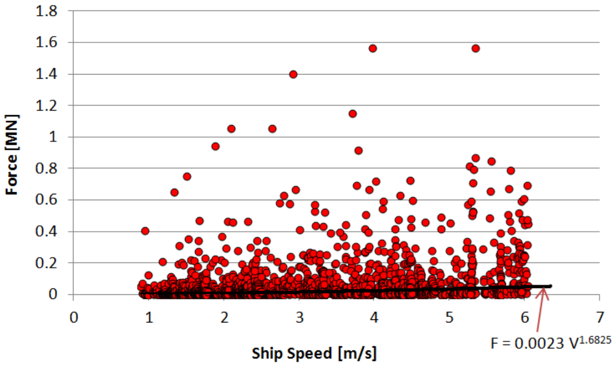


Figure 15. Plot of impacts forces vs. ship speed. (runs 46-50).

Figure 16 presents results for a specific subset of the collisions. Only those impacts on the first panel of the hull near the bow, and only those involving an impact with 0.7m thick floes are presented. Along with the GEM data is the solution for force vs. velocity for a collision with a 252t floe, with a 170deg. apex angle, both of which approximately represent the highest possible values in the simulation. This is a worst case combination, for which the flexural failure limit is also included. The data lies well within the bounds of the limit case.

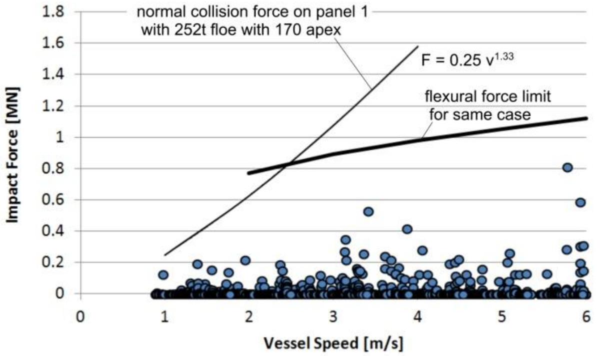


Figure 16. Plot of impacts forces vs. ship speed on panel 1 for 0.7m thick floes. (runs 46-50).

Load Level Statistics

The ice load statistics for several groups of runs appear to follow a Weibull distribution, especially at the upper end. Figure 17 shows the cumulative probability distribution data for a set of cases. Data labeled 121 is from runs 46-50. Data labeled 004 is from runs 16-20. Data labeled 040 is from runs 21-25. Data labeled 400 is from runs 26-30. The set labeled All is all of the above. In each case the coverage is 40%. In the case of 004 the ice thickness is 0.5m, or thin ice. In the 040 case the ice is all 0.7m thick, or medium ice. In the 400 case the ice is all 1.2m thick, or thick ice. In the 121 case there is 10% thick ice, 20% medium ice and 10% thin ice. In all cases the data has been modeled with a Weibull distribution, which has a cumulative distribution function;

$$F(x; k, \lambda) = 1 - e^{(x/\lambda)^k}$$

where x is the load in Newtons, k is the shape parameter and λ is the scale parameter. Figure 17 shows that the distributions are all very similar, though not identical as can be seen by examining the scale parameter for each data set. Loads are higher in the thicker ice, as would be expected. The remarkable thing is that the overall variation of the loads tend to mask the relatively small variations caused by thickness changes. The other sources of variation include velocity, floe size, floe apex angles and hull angles.

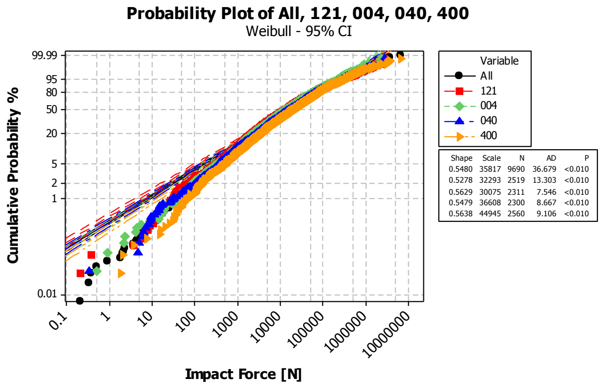


Figure 17. Probability plots of cumulative distribution of impacts forces. (runs 16-30 and 46-50).

Ice Load Statistics from Fields Trials Data

Ice impact load data has been gathered on a number of vessels. Figure 18 shows a map of the areas where ice impact load data have been collected on four different vessels. The *USCGC Polar Sea* conducted a series of western arctic trials in the 1980s (Daley, et. al. 1984, St. John et. al. 1985, Daley et al. 1990a,b). The *Polar Sea* had a load panel installed in its bow, large enough to capture impact loads as the ship struck ice floes. The data from those trials covers a wide variety of ice conditions, ranging from first year ice in the Bering Sea to heavy multi-year ice in the North Chukchi and Beaufort Seas, covering everything from open pack, to close pack, ridged and level ice. The *CCGS Louis S. St. Laurent* conducted a trans-Arctic voyage in 1997 and measured impact loads on panels similar to the arrangement on the *Polar Sea* (Rich et. al. 1997). The *Polar Sea* and *Louis St. Laurent* data had similar load measuring systems, and could measure the total impact force during a collision with an ice edge.

A Baltic ice class vessel called the *MS Kemira* was instrumented to measure frame loads (Kujala 1994, 1996,). The *Kemira* data was collected during normal commercial cargo voyages in first year sea ice in the northern Baltic. The *KV Svalbard*, a Norwegian Coast Guard vessel, was also instrumented to measure frame loads. Data was recorded in the Barents Sea in 2007 (Leira and Børsheim 2008, Leira et. al. 2009).

The data collected on these vessels represents a significant portion of the available scientific data concerning ice impact loads in sea ice. The data from these various trials will be discussed. It is important to consider that the vessels were of differing size and shape, operating in differing conditions, and with quite different sensor packages and levels of coverage.

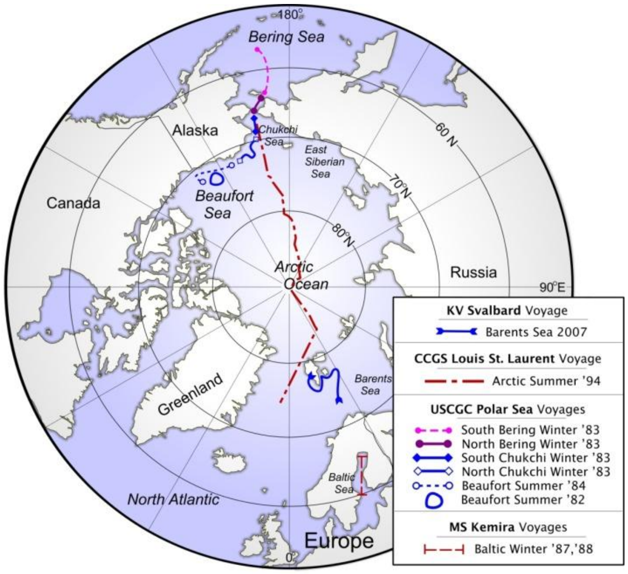


Figure 18. Arctic region map showing various ice loads ship trials.

The present authors have direct access to the raw measurement data from both the *Polar Sea* and the *Louis S. St. Laurent*. The authors do not have access to the raw data from the *Kemira* or *Svalbard*. However, analysis of the data from the *Kemira* and *Svalbard* has been published. The authors of those data sets have suggested that the data follows Weibull or similar (i.e. exponential) distributions. See Suominen and Kujala 2010 for analysis of *Kemira* data and Suyuthi et. al. 2012 for a discussion of *Svalbard* data.

Figure 19 shows some of the impact load data from the *Polar Sea* plotted as impact force vs. ship speed. Within one sea area there appears to be little obvious relationship between force and velocity, much as was observed in the GEM simulation (see e.g. Figure 15). It is interesting to note that in sea areas with lighter ice (Bering Sea) the vessel speeds were higher while the loads were lower than were the case in the regions of heavier ice (North Chukchi Sea). This is a natural result. For the present assessment it shows that loads are influenced by a combination of ice conditions and navigation practices.

Figure 20 shows impact load data from the 1994 Arctic Ocean voyage of the *Louis S. St. Laurent*. Once again there is no obvious trend between force and velocity, with a very slight inverse relationship when a single curve is fit to all data. The vessel transited a wide variety of conditions and so would have experienced similar navigation effects as discussed above.

It should be noted that the field data from the two vessels is subject to a number of artifacts that GEM data is not. Field data tends to be gathered with a threshold, such that all small load values are ignored. Also there is the problem of the completeness of the record. For both the *Polar Sea* and the *St. Laurent*, some of the load data did not have a corresponding velocity. All such data was plotted at a small velocity (.25m/s), which does obviously involve an error. The GEM simulation values are complete in all respects, with all impacts at all locations fully logged.

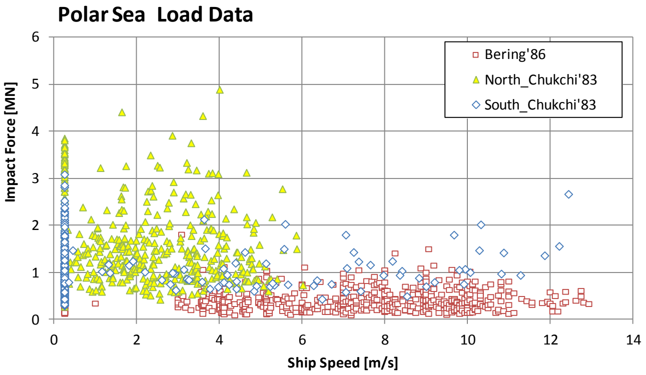


Figure 19. Ice impact load vs. ship speed from USCG POLAR SEA during 3 voyages.

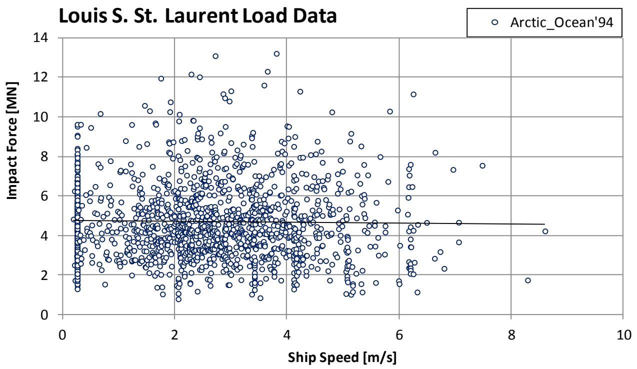


Figure 20. Ice impact load vs. ship speed from CCGS LOUIS S ST. LAURENT during a trans Arctic voyage in 1994.

Figure 21 shows one probability distribution for ice impacts on the *Polar Sea* in first year ice in the South Bering Sea. The data appears to show fluctuations which may be associated with varying ice conditions and interaction mechanisms. Nevertheless, the data is reasonably well described by a Weibull distribution.

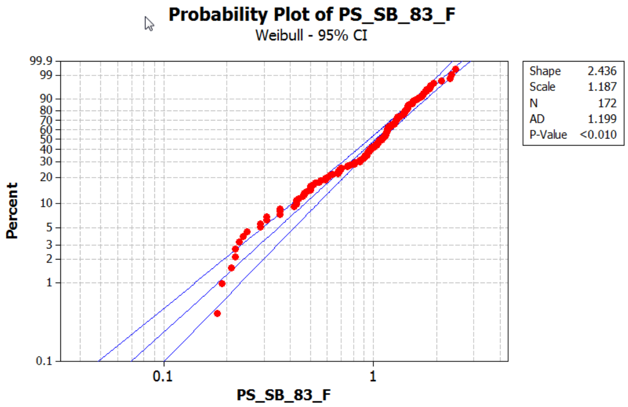


Figure 21. Ice impact load statistics for the POLAR SEA during its 1983 voyage in the first year ice of the South Bering Sea.

Discussion

Ship-ice interaction is a complex process, influenced by many nonlinear and some linear mechanical processes as well as by the many vessel design parameters and the navigation practices. Developing an understanding of the process is a challenge that requires the integration of many approaches. Full scale data is crucially needed to provide direct knowledge of the process and to allow validation of the models and theories used to describe the process. Unfortunately full scale data is both limited and imperfect. Conventional numerical modeling approaches have tended to focus on either the local mechanics or the broad system level, often leaving these two types of models somewhat disconnected.

In this paper we have presented results from a new development we call GEM (GPU-Event Mechanics). The approach allows us to follow the movement of the vessel (s) and the ice floes for a long period of time, even while we include all the individual collision and contact events. By combining the modeling of short term events and long term kinematics, the model accounts for system level behavior without the need to overly simplify the kinematics and impacts. It is intended to expand on the range of events covered and to improve the sophistication of the kinematics.

The paper presents a number of new insights into some questions of interest. One is the question of the statistical nature of ice loads. This analysis has shown that while ice thickness does influence load, through its influence of mass and flexural strength, the main cause of variations shown here is due to the variable ice mass and apex angle. While this is far from definitive, it is a useful insight. In many situations the ice thickness does not vary over orders of magnitude while the loads often do. The GEM program can be a useful tool in exploring the sources of variability in the loads, helping to establish a better understanding of the statistics, especially at the extreme or design levels.

Another useful result is shown in Figure 13. While one might expect that a ship in uniform pack ice would experience a similar impact rate per meter of breadth anywhere in the bow, the GEM results are showing a kind of shadowing effect. This is possible because all ice floe motions and interactions are being tracked. Further studies of a wider range of ice conditions, combined with more realistic navigation strategies would help to explain both the rate of collisions and also the appropriate design loads for various parts of a vessel. The question of the validity of the hull area factors used in ice class structural design is of great practical significance.

Figures 15 and 16 show the GPU results for force as a function of speed. As is typical of full scale data (Figures 19, 20) the effects of speed are lost in the general scatter. The field data and even the GEM data show no obvious limits (upper bounds). Nevertheless, the GEM model mechanics have very specific limits that are so rarely reached that they are not evident. Most statistical models assume open tail distributions, and so may predict extreme design values higher than may be physically possible. The GEM model can easily be used with probabilistic as well as deterministic inputs, and would be able to explore this question, and remove unnecessary conservatism. Any excessive conservatism, is costly and tends to undermine potential improvements in other aspects of a design.

Further Work and Conclusion

The GEM model is a work in progress. The version discussed here tracks a single vessel through a simple open ice pack. As of this writing additional features have already been implemented including;

- Floe edge flexural failure, with new floe creation
- Wind loads on floes
- Current forces on floes

Further enhancements are being planned that will add;

- Rafting behavior (2.5D)
- Floe Splitting
- Simplified Ridging at floe-floe contacts

The above enhancements can be implemented in the current 2.5D model. To take the technology to an entirely new level, the modeling will need to be implemented in a full 3D framework.

The above discussion and results has described a new class of model that integrates a number of old ideas into a new capability. The recent developments in GPU computation have permitted the modeling of a massive event set in faster than real time, using affordable desktop computer hardware. With demands for greater safety and greater understanding of ship and structure operations in polar regions, there is a need for new simulation tools. The GEM approach permits the user to model complex problems in a timely and practical way. Much more development and validation is still required but the authors feel that the first steps have been successful.

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