Simulation of Managed Sea Ice Loads on a Floating Offshore Platform using GPU-Event Mechanics

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ABSTRACT

The paper describes a GPU-based event mechanics (GEM) model of the action of managed pack ice on a floating offshore structure. The ice cover is represented by a large number of discrete polygonal ice floes, of varying thickness. Each ice-structure contact is modeled, as is every ice-ice contact. Time histories of total platform force (net mooring force) and platform position are presented. Ice coverage, floe sizes and thickness are varied in the simulation set. The work represents a further exploration of the possibilities of GEM technology, which was previously used to explore both resistance and local structural loads for ships transiting pack ice. The work is part of a research project at Memorial University of Newfoundland called STePS^2 (Sustainable Technology for Polar Ships and Structures).

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

INTRODUCTION

The paper presents preliminary results concerning the use of GPU-event mechanics (GEM) computer technology to simulate the response of a moored drill barge to drifting pack ice, as an approximation of managed ice.

The problem explored here is interaction of loose pack ice comprised of small floes drifting onto a moored platform. Figure 1 illustrates the sort of full scale situation envisaged, except that Figure 1 involves a DP drillship rather than a moored drill barge. As the broken floes drift past the platform, they will collide and rub against each other and the platform. A very large number of interactions will occur, both between the floes and to the platform. Moored drill ships have quite long horizontal plane natural periods, of the order of 90 seconds. This implies that only simulations of much longer than 90 seconds have a chance of displaying the realistic platform response to loads.

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 computational speeds up to 6x real time.

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Figure 1. Drilling in managed pack ice at North Pole, 2004.

Another aim of the paper is to explore a new use of the GPU-Event-Mechanics (GEM) simulation approach. The GEM approach integrates several concepts. The physical space is described as a set of bodies. The movements (kinematics) of the bodies are 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 basic collision event was originally developed to represent the design scenario in the IACS Polar Rules (Daley 2000). That event was based on a method developed by Popov et al. (1967), updated with a pressure-area model. The models were extended further to permit direct design of polar ships (Daley 1999, 2001, Daley et. al. 2007 and Daley and Kendrick 2008). The GEM model takes the event concept and implements it in a massively parallel multi-body interaction simulation. The GEM model combines the event concept with the massively parallel computation power of GPUs. 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, 2014) 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. As a rough comparison, the results presented here represent about 72 hrs of real-time interaction and took about 36hrs to compute on a GPU card costing less than $1000. If all the collisions could have been calculated as continuum events in LS-Dyna (which was used to study single events) the total computation time on a standard desktop computer would be in the range of 10,000 to 100,000 years. The GEM model focuses on the large scale system involving a large number of bodies, rather than on any single impact. This feature has great practical significance for design, assessment and training applications.

MODEL INPUT

Ice Conditions

The 36 simulations discussed below were performed in ice fields with three types of concentrating boundaries and 3 different current speeds. All the fields involved the same set of 4008 randomly shaped and oriented polygons representing ice of 4/10ths concentration (see Figure 3). The thickness of the floes was set to be 1.2m, 0.7m or 0.5m (thick, medium and thin first year ice). In one case there was a mix of 1/10 thick, 2/10 medium and 1/10 thin ice. In the other cases all the ice was of one thickness.

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 4). 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 of several of the floes in an image of pack ice and then making multiple 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 start with no floes in contact with any other floes.

The intention of the investigation has been to simulate a simple case of managed ice (or natural pack in small floes). Figure 2 illustrates a situation in which ice is broken upstream of a platform by an icebreaker and drifts toward the platform. Figure 3 shows the simulation domain including a rectangular region 1500m x 400m consisting of 4008 floes upstream of the platform. There are two fixed boundary objects that are 400m apart at one end and may taper towards the platform. In the case shown the gap at the platform is 300m. Gap widths of 400m, 300m and 200m were used. The fixed boundaries can be thought to represent the edge of unbroken ice, although they were included as a simple way to increase the concentration of ice acting on the platform.

When the simulation starts, the ice begins to drift towards the platform due to the action of a current. The ice floes quickly begin to drift at the current speed, and do so until they impact the platform or other floes.

Platform Description

The platform used in the simulation is a circular drill barge with the following nominal properties:

Diameter: 100m
Waterline shape: vertical
Mass: 100,000 tonnes
Mooring Stiffness: 500 kN/m (linear, both x and y)
Geometry: 2D polygon (20 sided)

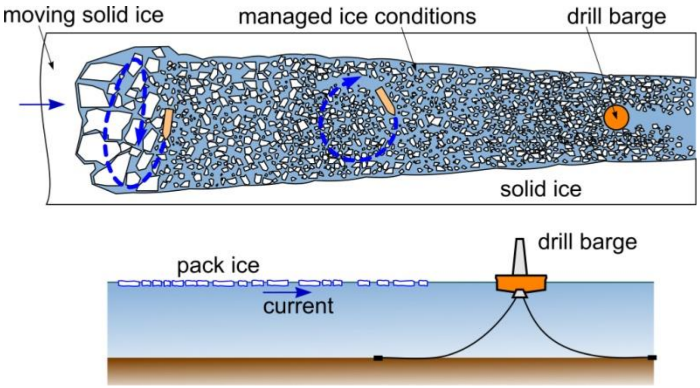
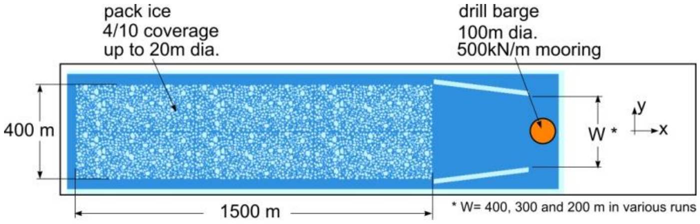


Figure 2. Concept sketch of simulation.



* W= 400, 300 and 200 m in various runs

Figure 3. Actual geometry of 2D simulation domain

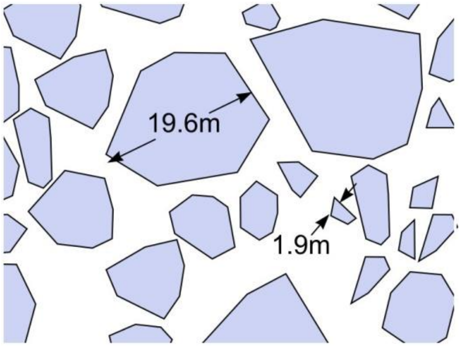


Figure 4. Close-up of Random Polygonal ice floes

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 is only the current driving force but no wind. Neither are there any of the more complex responses such as rafting and rubbling. These are being planned for future generations of the model.

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 ice contact 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.

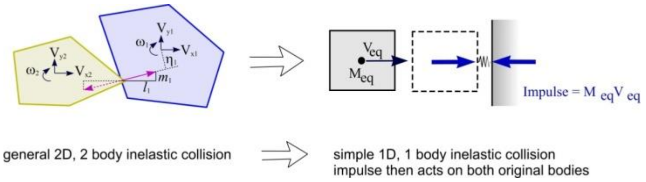
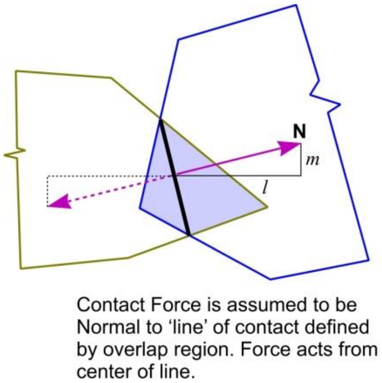


Figure 5. Idealization of 2D collision between two finite bodies.



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

Figure 6. 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. 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.

Platform Behavior

The platform is modeled as a floating body subject to ice impact forces, inertial forces and a simple mooring restoring force. In most of the simulations, the water drag (damping) in the platform was ignored. Two simulations (1c and 1e) were done with water drag to see the effect of this assumption.

SIMULATION CASES

The basic set of simulation runs is tabulated in Table 1, showing the ice thickness, boundary width and current speed parameters. Table 2 lists 5 additional alternative runs that were all based on run #1. These alternatives were used to see if the model was behaving as might be expected, as a check. The results of these check runs is described below.

Table 1. List of simulation run parameters.

#	Runs	Cthk 1/10th	Cmed 1/10th	Cthin 1/10th	W m	Current m/s
1	004_400_25	0	0	4	400	0.25
2	004_400_50	0	0	4	400	0.50
3	004_400_100	0	0	4	400	1.00
4	004_300_25	0	0	4	300	0.25
5	004_300_50	0	0	4	300	0.50
6	004_300_100	0	0	4	300	1.00
7	004_200_25	0	0	4	200	0.25
8	004_200_50	0	0	4	200	0.50
9	004_200_100	0	0	4	200	1.00
10	040_400_25	0	4	0	400	0.25
11	040_400_50	0	4	0	400	0.50
12	040_400_100	0	4	0	400	1.00
13	040_300_25	0	4	0	300	0.25
14	040_300_50	0	4	0	300	0.50
15	040_300_100	0	4	0	300	1.00
16	040_200_25	0	4	0	200	0.25
17	040_200_50	0	4	0	200	0.50
18	040_200_100	0	4	0	200	1.00
19	400_400_25	4	0	0	400	0.25
20	400_400_50	4	0	0	400	0.50
21	400_400_100	4	0	0	400	1.00
22	400_300_25	4	0	0	300	0.25
23	400_300_50	4	0	0	300	0.50
24	400_300_100	4	0	0	300	1.00
25	400_200_25	4	0	0	200	0.25
26	400_200_50	4	0	0	200	0.50
27	400_200_100	4	0	0	200	1.00
28	121_400_25	1	2	1	400	0.25
29	121_400_50	1	2	1	400	0.50
30	121_400_100	1	2	1	400	1.00
31	121_300_25	1	2	1	300	0.25
32	121_300_50	1	2	1	300	0.50
33	121_300_100	1	2	1	300	1.00
34	121_200_25	1	2	1	200	0.25
35	121_200_50	1	2	1	200	0.50
36	121_200_100	1	2	1	200	1.00

Table 2. List of alternative run parameters.

#	Runs	Mooring Stiff kN/m	Water Drag on Platform	Note
1	004_400_25	500	no	
1a	004_400_25(2)	500	no	re-run #1 as is
1b	004_400_25_F	500	no	re-run #1 w/ **ice forces** extracted
1c	004_400_25_WD	500	yes	re-run #1 water drag on OS
1d	004_400_25_50kND	50	no	re-run #1 at 50kN w/o water drag on OS
1e	004_400_25_50k_WD	50	yes	re-run #1 at 50kN w/water drag on OS

MODEL RESULTS

A few example outputs are shown below to illustrate the type of data available from the model.

Field Images

Figure 7 shows an image of the 004_400_25 simulation
In this case the current moves the ice pack towards and around the structure. In the image, color represents velocity. The ice plug ahead of the structure is clearly visible. Further upstream the ice stays uniformly spaced as it is uniformly dragged by the current. The ice behind the structure has been forced to interact and has randomly dissipated forming clusters. At this scale the platform movement is so small that it is not easily evident in the video.

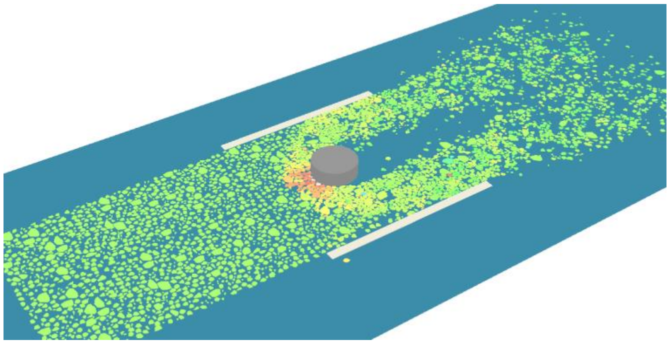
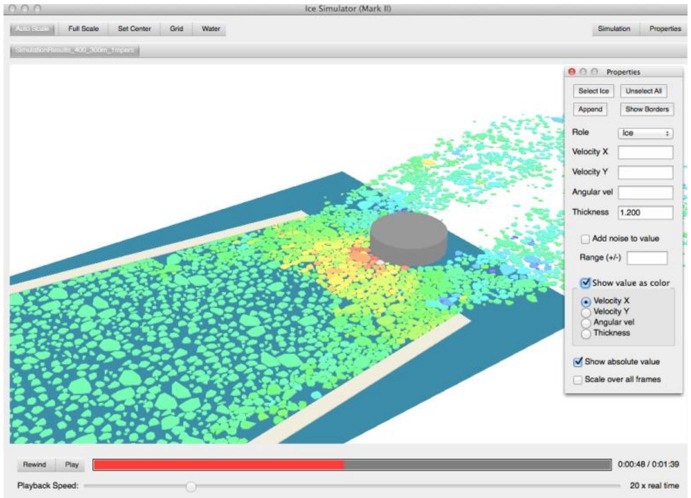


Figure 7. Image from 004_400_25 simulation

Figure 8 shows another simulation, with the barriers acting to direct the ice towards the platform. The ice tends to become more concentrated by the barriers, and forms approximately 9/10th coverage. The figure also shows the full user interface, with the property information to the right, the video controls at the bottom and the general user buttons at the top.



Role: Ice
Velocity X
Velocity Y
Angular vel
Thickness: 1.200
☐ Add noise to value
Range (+/-)
☑ Show value as color
● Velocity X
○ Velocity Y
○ Angular vel
○ Thickness
☑ Show absolute value
☐ Scale over all frames
0:00:48 / 0:01:39
Playback Speed: 20 x real time

Figure 8. Image from 400_300_100 simulation

Time Sequence Results

Figure 9 shows the platform response to the drifting ice in the 004_400_25 case. This case represents drifting 4/10th thin FY ice (0.5m thick) at 0.25m/s against the structure for approximately 2 hours. The side barriers were left parallel so that no concentrating effect occurred. The figure shows interesting features. The main oscillation has a period of approximately 72 seconds. The expected period was 89 seconds (based on the platform mass and mooring stiffness). It is also clear that the oscillation amplitude varies somewhat randomly. For this run, there was no water drag on the platform (only on the ice) and so the platform was both loaded and damped by the ice interaction. It is also interesting that the platform oscillated upstream and downstream, with little obvious mean offset. A steady offset due to the ice might have been expected. There appears to be a slight change in behavior around the one hour mark.

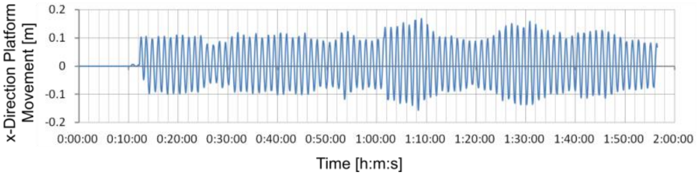


Figure 9. Time-history of platform movement in the x direction (run 004_400_25).

Figure 10 shows the y-direction movement of the platform, which is quite different from the x-direction movement. The initial amplitudes are much larger and then change abruptly at around the one hour mark. Figure 11 shows the movement of the platform in the x-y plane. The orbits are not steady. This behavior looks like the typical response of non-linear dynamic systems (termed chaos), with orbits changing from one type to another. The non-linearity is the result of the ice floe collisions. Each collision adds or removes energy depending on the relative velocities of the colliding bodies. If the system is chaotic, it should have other known properties of chaotic systems, such as a tendency to lose information as it proceeds.

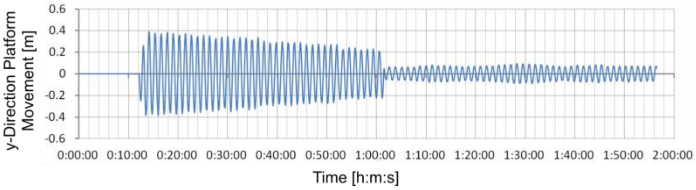


Figure 10. Time-history of platform movement in y direction (run 004_400_25).

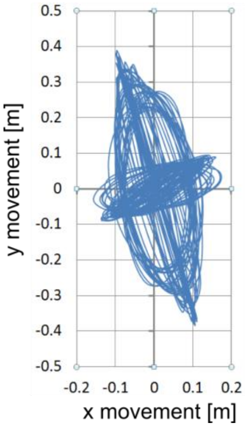


Figure 11. x-y position of platform shown as orbit paths (run 004_400_25).

Figure 12 shows two simulations that were essentially the same. The two time histories start out the same and continue so for almost an hour. But then the two records diverge. This loss of pattern is typical of chaotic systems and results from a slow loss of positional information due to the non-linear events that occur.

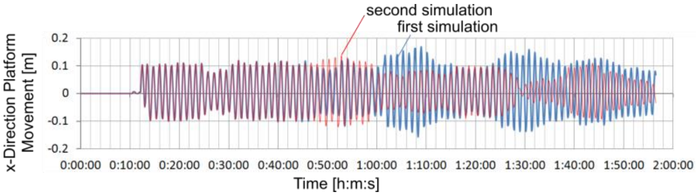


Figure 12. Comparison to simulations with identical properties (runs 004_400_25 and 004_400_25(2)).

Figure 13 shows the platform response to the drifting ice in the 400_300_100 case. This case represents drifting 4/10th thick FY ice (1.2m thick) at 1.00m/s against the structure for approximately 40 minutes. The side barriers were angled to create a concentrating effect. Note the difference from Figure 9. Figure 14 shows the movement of the platform in the x-y plane. The orbits are still chaotic, but the mean offset is now more obvious. In both these cases, as with all cases simulated, the largest mooing loads were much larger than would have been caused by the mean ice load. As well, the chaotic nature of the platform response implies that its behavior cannot be evaluated on the basis of short term simulation. Even the several hours of these simulations are likely not long enough to fully capture the range of responses for any given ice condition. Chaotic systems are somewhat like random systems, though they are characterized by a different form of variability. Conventional statistical distributions may not be the most appropriate for such cases. Chaotic systems are typically bounded and with most statistical models being open ended there can be problems when modeling extreme responses. This is an area that deserves much more study.

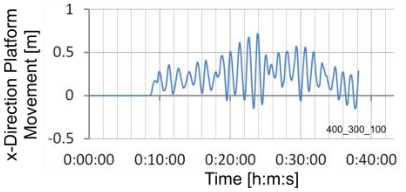


Figure 13. Time-history of platform movement in the x direction (run 400_300_100).

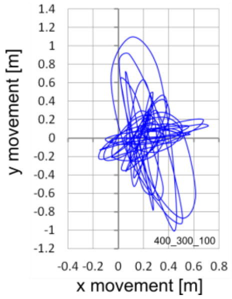


Figure 14. x-y position of platform shown as orbit paths (run 400_300_100).

Local Ice Impact Forces

Figure 15 shows a record of the ice impact forces on the platform for the 004_400_25 case. The values represent the net x-direction ice contact force, summed from any contacts that are occurring at that moment. The lower record is for the entire 2 hour duration, while the upper trace is a short 33 second extract. The model simulates a very large number of events with each event reflecting the specific geometric and mechanical conditions that apply at that moment.

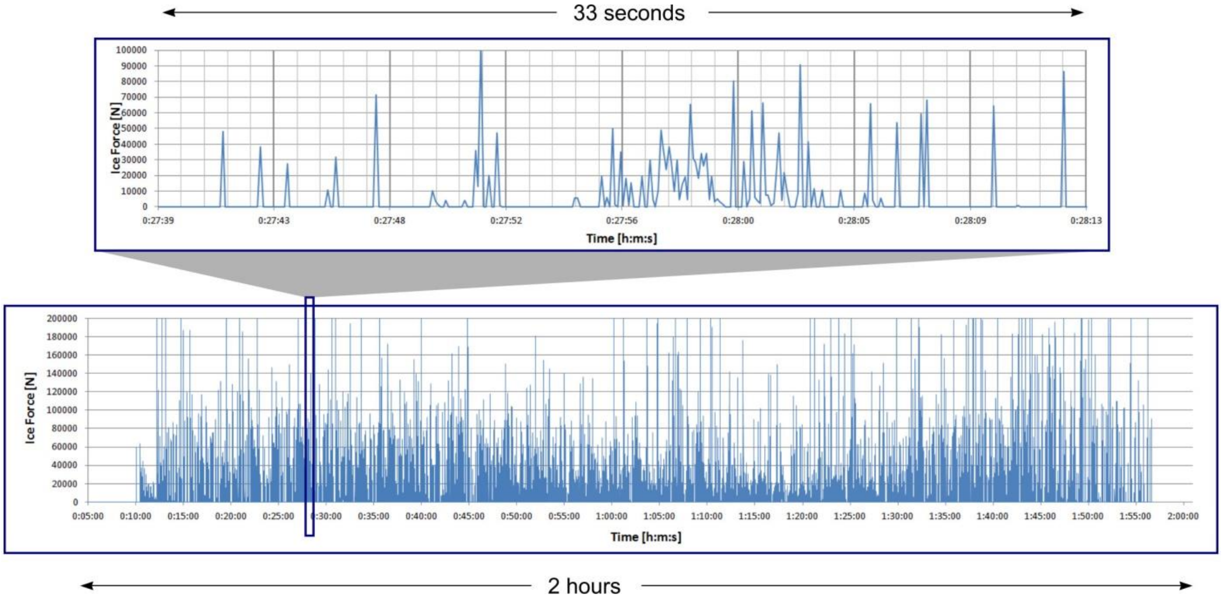


Figure 15. Time-history of ice contact force (net x-direction) for the 004_400_25 case.

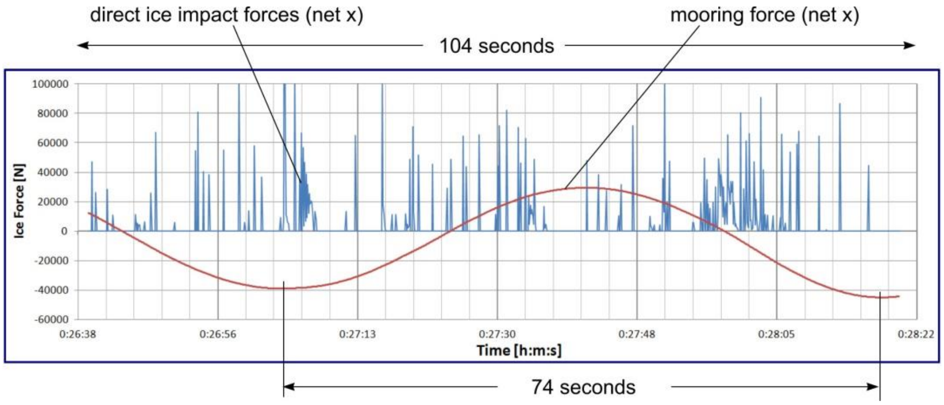


Figure 16. Time-history of ice contact force compared with mooring system force (net x-direction) for the 004_400_25 case.

Figure 16 shows a comparison of the local ice forces with the global mooring force response. Clearly the two records are very different. The peak ice loads far exceed the peak mooring loads, while the peak mooring loads far exceed the mean ice loads. Of course this is a case of relatively light and open pack ice. In cases of heavier ice these relationships may vary substantially.

Total Platform Excursions

For each simulation case, the total maximum excursion was found. Figure 17 shows the values in 4/10 thin ice. Figure 18 shows the values in 4/10 medium ice. Figure 19 shows the values in 4/10 thick ice. Figure 20 shows the values for a mixture of thin, medium and thick ice. The results show that there is a general trend of higher motions in thicker and more concentrated ice. The scatter is probably due to the relatively short durations of the simulations. For the values to reach comparable maxima, simulations of possibly 24 hrs might be needed.

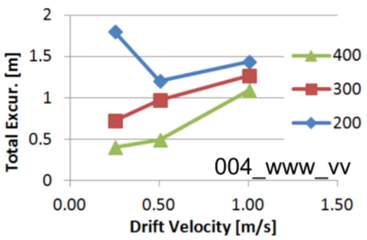


Figure 17. Plot of maximum platform excursion vs drift velocity for the 004_www_tt cases.

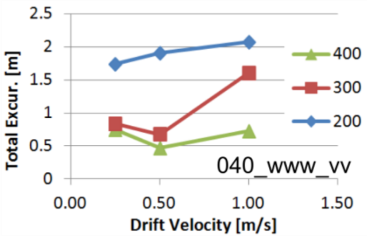


Figure 18. Plot of maximum platform excursion vs drift velocity for the 040_www_tt cases.

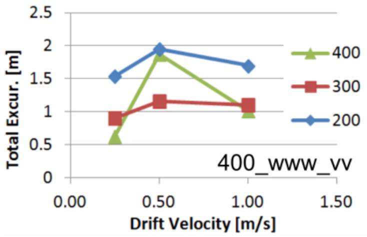


Figure 19. Plot of maximum platform excursion vs drift velocity for the 400_www_tt cases.

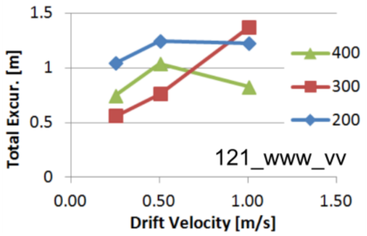


Figure 20. Plot of maximum platform excursion vs drift velocity for the 121_www_tt cases.

DISCUSSION AND RECOMMENDATIONS

The simulation results presented above show another example of the potential for use of GEM simulation for problems in ice mechanics. Earlier applications have covered ship resistance in pack ice and local ice loads statistics on ships in pack ice. This application has explored the nature of the response of a moored offshore platform to drifting ice. This ice could be thought of a managed ice because of the lack of larger features.

The results have shown some interesting and somewhat unexpected results. The mooing line loads have a very different character from the ice loads. The platform responded as a simple oscillator, but not one exhibiting simple oscillatory response to an oscillatory input or to random noise. The system appears to behave chaotically. This result calls for additional study to explore both the full range of responses and to understand the link between the ice conditions and the response. One optimistic aspect is that the response appears to be bounded. It may be that the details of the ice interaction may damp the higher amplitudes of response but this is merely speculation at this point.

One thing that seems clear is that the response to a moored platform in light ice is far from simple. One strong feature of the GEM approach is the ability to model very long duration events. This appears to be important if the full range of responses is to be studied

Future work on the GEM software will involve an increase in the number and complexity of modeled systems. The inclusion of both multiyear ice and ice rubble is needed to model more extreme conditions. Improvements in the mooring and hydrodynamic aspects of the model would be useful. And a study of the response of a DP platform would be most interesting, especially for cases in which larger solo hazards are included. The GEM model operates with simple deterministic mechanics. Some model properties (floe size and shape) represent a random variation, while others (thickness, strength, edge profile) do not. It would be useful to explore the inclusion of greater model input variability.

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