Observations on the Modeling of Ice FloeInteractions with Seakeeping Software

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Abstract

An investigation of the capabilities of a suite of seakeeping software to model the interactions of ice floes and icebreaking hull forms was initiated, as part of a wider investigation into arctic operations. The sea keeping behavior of a systematic series of ice floes with variations in area extent and thickness, acting alone and in groups is analyzed and presented.

This investigation focuses on developing a methodology that can be used in the preliminary and later stages of ship design for ice infested waters. A number of sensitivity studies were performed that explore the limitations and features of the several software packages available to the authors.

Introduction

This paper is organized into several distinct but related parts.

- Linear ship motion theory Response Amplitude Operators (RAOs) are developed for 5 different sizes of ice flow and for 5 different thicknesses for a 10m square flow. This utilizes the WADAM panel code model described more completely in the appendix.
- The statistical responses of these ice floes to typical waves is investigated and described.
- A non-linear WASIM panel code model that uses exactly the same input panelization as the WADAM model, was used for a range of wave azimuth conditions to create comparable data. This modeling also allows the 3 axis shear and bending stresses on the floe due to waves to be evaluated in a non-linear time series.
- Two patterns of multiple floes with leads between them were modeled in the WADAM model and summary responses to waves along a sample transect through this ice field were modeled.
- A notional vessel reinforced to ABS Baltic Ice Rules, class 1A was placed into an ice field in the OrcaFlex model and run with forward speed through the ice to see if icebreaking can be easily simulated.

The paper then summarizes the findings of the various component studies, and concludes with a discussion of plans to expand this modeling capability in the future.

Data Availability

The linear and non-linear motions, shear stresses and bending moments data developed for these ice floes is available to other investigators to support other studies. Interested parties are invited to contact the authors at skery@csc.com.

Interactive models of the data are also available at Tableau Public. https://public.tableau.com/profile/logan.wilt#!/vizhome/IceFlowInteractions/Observations

Data containing specific ship information cannot be shared due to the proprietary hull form.

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Single Ice Floe Analyses

Table 1: Sizes and Masses of Ice floes used in this study

Floe Size									
Length & Width (m)	10	10	10	10	10	25	50	100	250
Thickness (m)	1	1.5	2	2.5	3	1.5	1.5	1.5	1.5
Volume (m^3)	100	150	200	250	300	937.5	3750	15000	93750
Water line draft (m)	0.6	0.9	1.2	1.5	1.8	0.9	0.9	0.9	0.9
Mass (kg)	60000	90000	120000	150000	180000	562500	2250000	9000000	56250000
Mass (M-tonnes)	60	90	120	150	180	562.5	2250	9000	56250
Mass Multiplier	1	1.5	2	2.5	3	9.375	37.5	150	937.5
Area Multiplier	1	1	1	1	1	6.25	25	100	625
Diagonal Length	14.1421	14.1421	14.1421	14.1421	14.1421	35.3553	70.7107	141.421	353.5534
Flat Natural Period	2.53	2.53	2.53	2.53	2.53	4.00	5.66	8.00	12.66
Diagonal Natural Period	3.01	3.01	3.01	3.01	3.01	4.76	6.73	9.52	15.05

Table 1 shows the mass of the 9 different floes modeled and the natural periods "flat side on" and "diagonal point on" to the wave direction, based upon the deep water wave equation when the floe length equals the wave length. The maximum heave, pitch and roll motions will probably occur when the wave length is twice the floe dimension such that one end is at the maximum peak while the other is at the minimum trough.

These sizes were chosen to represent first year ice floes in and around the ice edges where waves may be encountered. In most cases it was necessary to round two of the corners to a constant radius to get the panel mesh to close.

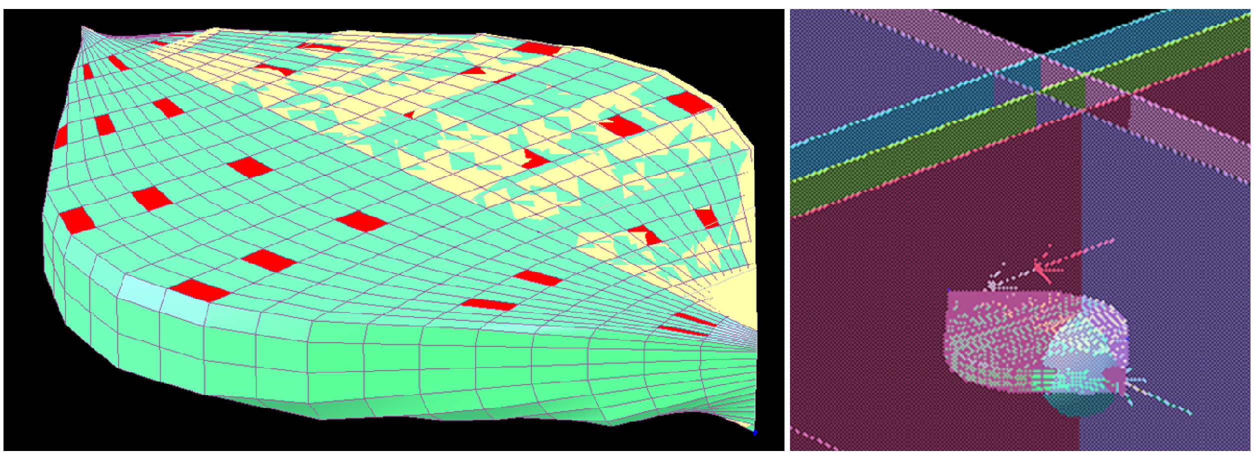


Figure 1: 10m^2 Flow with Rounded Corners and Stress Cuts

Figure 1 shows the mesh in the WADAM and WASIM seakeeping programs for a typical 10m square floe. The same radius was used for all sizes so it has less of an effect on the larger floes.

The right hand pane shows a series of 5 cuts through the shape. There are 3 transverse / vertical cuts at the 1/4, 1/2, 3/4 length points and 2 longitudinal / vertical cuts at the half width and 1/3 rd width points. The programs calculate the 3 axis shear and 3 axis rigid body bending moments at each of these cuts. The WASIM results are described later in this paper. The WADAM and WASIM RAO based results have not been post processed into usable form at this time although that has been done successfully on other projects.

Single Floe RAO Motion Variation with Area Extent

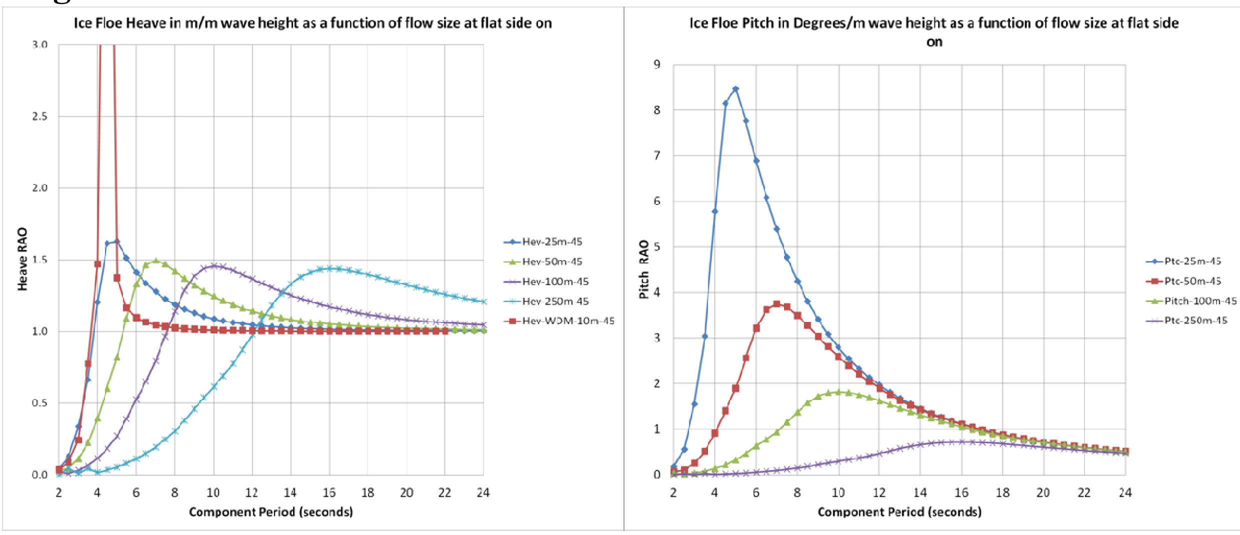


Figure 2: RAO Plot at 45 degrees Showing Behavior with Floe Size

Figure 2 shows the vertical plane motion in heave and the roll or pitch RAO's for each of the 5 floe sizes. These plots show that there is a marked difference in rigid body motions with floe size / area extent.

The $10m^2$ RAO is omitted for the pitch / roll RAO because the resonant peak is very high and the scale is lost for the other floes, when it is included. For a square flow the roll and pitch motions should be the same.

Single Floe RAO Motion Variation with Thickness

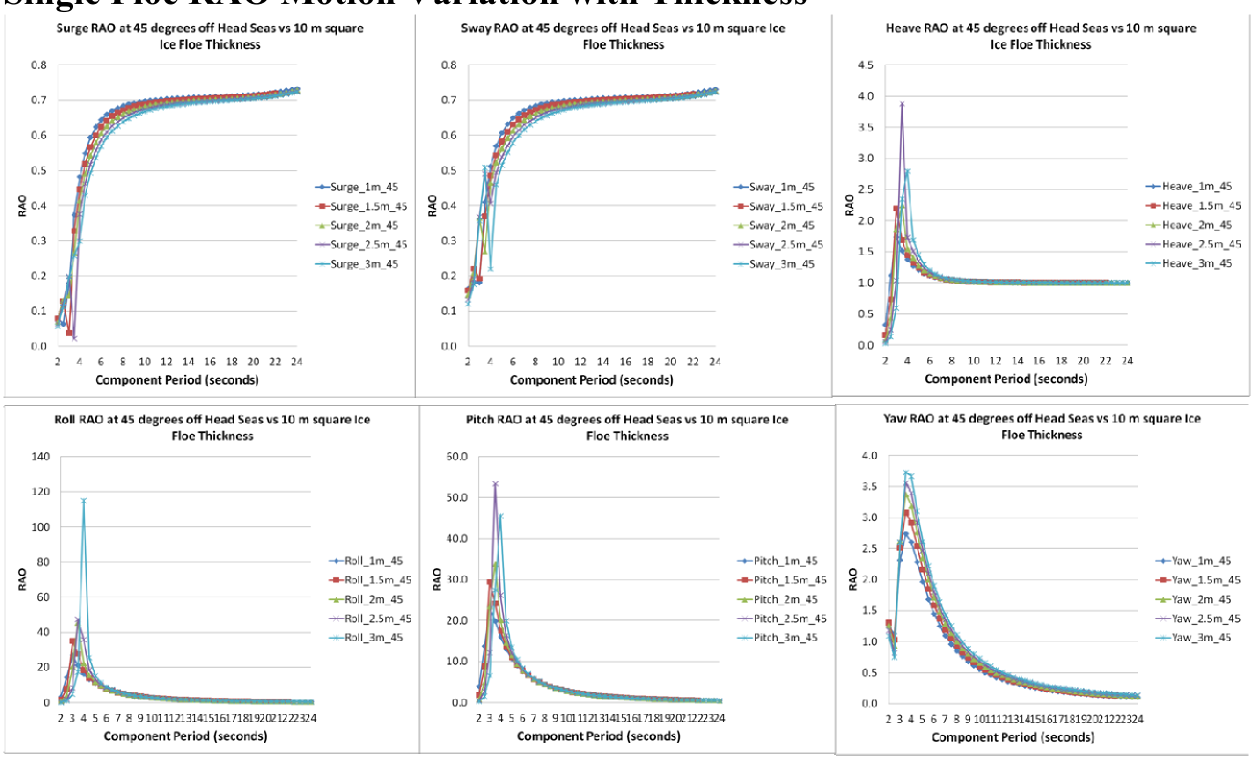


Figure 3: Single 10m Floe RAO's for 5 Thickness Values

Figure 3 shows that the floe behavior in waves is only weakly affected by thickness over the 1 to 3m thickness band tested.

The RAO's presented so far are linear theory frequency dependant transfer functions squared. While they tell us some things about how the ice floe will behave in waves, it is necessary to perform a convolution integral with a wave spectrum in order to achieve what the likely response will be. Table 2 shows part of a response spreadsheet.

Table 2: Example Response Table

RMS							
Speed	Tm =	6.43	H1/3 =	1.00			
knots	Heading	Srg-100m-1m	Sway-100m-1m	Hev-100m-1m	Roll-100m-1m	Ptc-100m-1m	Yaw-100m-1m
0	0	0.04	0.00	0.19	0.00	0.34	0.00
0	15	0.04	0.01	0.19	0.10	0.35	0.01
0	30	0.04	0.02	0.20	0.19	0.35	0.02
0	45	0.03	0.03	0.20	0.27	0.35	0.02
0	60	0.02	0.05	0.18	0.33	0.31	0.03
0	75	0.01	0.06	0.13	0.37	0.13	0.03
0	90	0.00	0.06	0.05	0.38	0.00	0.00
0	105	0.01	0.06	0.09	0.37	0.13	0.03
0	120	0.02	0.05	0.13	0.33	0.31	0.03
0	135	0.03	0.04	0.16	0.27	0.35	0.02
0	150	0.04	0.03	0.16	0.19	0.35	0.02
0	165	0.04	0.01	0.16	0.10	0.35	0.01
0	180	0.04	0.00	0.16	0.00	0.34	0.00

RMS							
Speed	Tm =	12.36	H1/3 =	1.00			
knots	Heading	Srg-100m-1m	Sway-100m-1m	Hev-100m-1m	Roll-100m-1m	Ptc-100m-1m	Yaw-100m-1m
0	0	0.18	1.00	0.36	0.30	0.44	0.00
0	15	0.17	1.05	0.34	0.13	0.43	0.02
0	30	0.15	1.09	0.31	0.26	0.40	0.03
0	45	0.13	1.13	0.31	0.37	0.35	0.04
0	60	0.09	1.16	0.27	0.45	0.27	0.04
0	75	0.05	1.18	0.21	0.50	0.15	0.03
0	90	0.00	1.19	0.16	0.52	0.00	0.00
0	105	0.05	1.18	0.21	0.50	0.15	0.03
0	120	0.09	1.17	0.24	0.45	0.27	0.04
0	135	0.13	1.13	0.26	0.37	0.35	0.04
0	150	0.15	1.09	0.32	0.26	0.40	0.03
0	165	0.17	1.05	0.34	0.13	0.43	0.02
0	180	0.18	1.00	0.34	0.30	0.44	0.00

RMS							
Speed	Tm =	7.39	H1/3 =	1.00			
knots	Heading	Srg-100m-1.5m	Sway-100m-1.5m	Hev-100m-1.5m	Roll-100m-1.5m	Ptc-100m-1.5m	Yaw-100m-1.5m
0	0	0.12	0.00	0.48	0.00	0.51	0.00
0	15	0.11	0.03	0.48	0.23	0.51	0.02
0	30	0.11	0.06	0.48	0.45	0.51	0.04
0	45	0.09	0.09	0.48	0.63	0.50	0.06
0	60	0.07	0.13	0.42	0.78	0.48	0.06
0	75	0.04	0.15	0.30	0.88	0.31	0.07
0	90	0.00	0.16	0.15	0.91	0.00	0.00
0	105	0.04	0.16	0.22	0.88	0.31	0.07
0	120	0.07	0.14	0.32	0.78	0.48	0.06
0	135	0.09	0.11	0.38	0.63	0.50	0.06
0	150	0.11	0.07	0.41	0.45	0.51	0.04
0	165	0.11	0.04	0.42	0.23	0.51	0.02
0	180	0.12	0.00	0.42	0.00	0.51	0.00

RMS							
Speed	Tm =	14.17	H1/3 =	2.00			
knots	Heading	Srg-100m-1.5m	Sway-100m-1.5m	Hev-100m-1.5m	Roll-100m-1.5m	Ptc-100m-1.5m	Yaw-100m-1.5m
0	0	0.37	1.00	0.71	0.30	0.85	0.00
0	15	0.36	1.10	0.72	0.26	0.84	0.03
0	30	0.33	1.19	0.67	0.50	0.78	0.06
0	45	0.27	1.28	0.62	0.70	0.68	0.08
0	60	0.20	1.34	0.54	0.36	0.52	0.08
0	75	0.10	1.38	0.44	0.27	0.29	0.06
0	90	0.00	1.40	0.36	1.30	0.00	0.00
0	105	0.10	1.39	0.41	0.37	0.29	0.06
0	120	0.20	1.35	0.51	0.36	0.52	0.08
0	135	0.27	1.28	0.56	0.70	0.68	0.08
0	150	0.33	1.20	0.64	0.50	0.78	0.06
0	165	0.36	1.10	0.67	0.26	0.84	0.03
0	180	0.37	1.00	0.68	0.30	0.85	0.00

The partial spreadsheet shown in table 2 was built out for ship motions studies so the first column is the vessels speed, which in the case of ice flows is zero or nearly so.

The second column is the direction that the waves are coming from in 15 degree increments with zero degrees being following seas and 180 degrees being head seas.

The authors have created a Matlab program that reads the RAO's for all 13 azimuth settings and 45 spectral components and then convolutes that with 21 different Bretschneider Spectra to produce a 3 modal period, by 7 significant wave height, matrix of responses.

All of the values are output as the Root Mean Square (RMS) value, achieved by performing the convolution integral using a trapezoidal rule method and spectral moments. Table 2 shows 4 of the 21 available instances. Typically, the 3 modal periods are chosen from the NATO STANAG 4194, Table D2, for the 5% 50% and 95% most likely modal periods for each wave height selected.

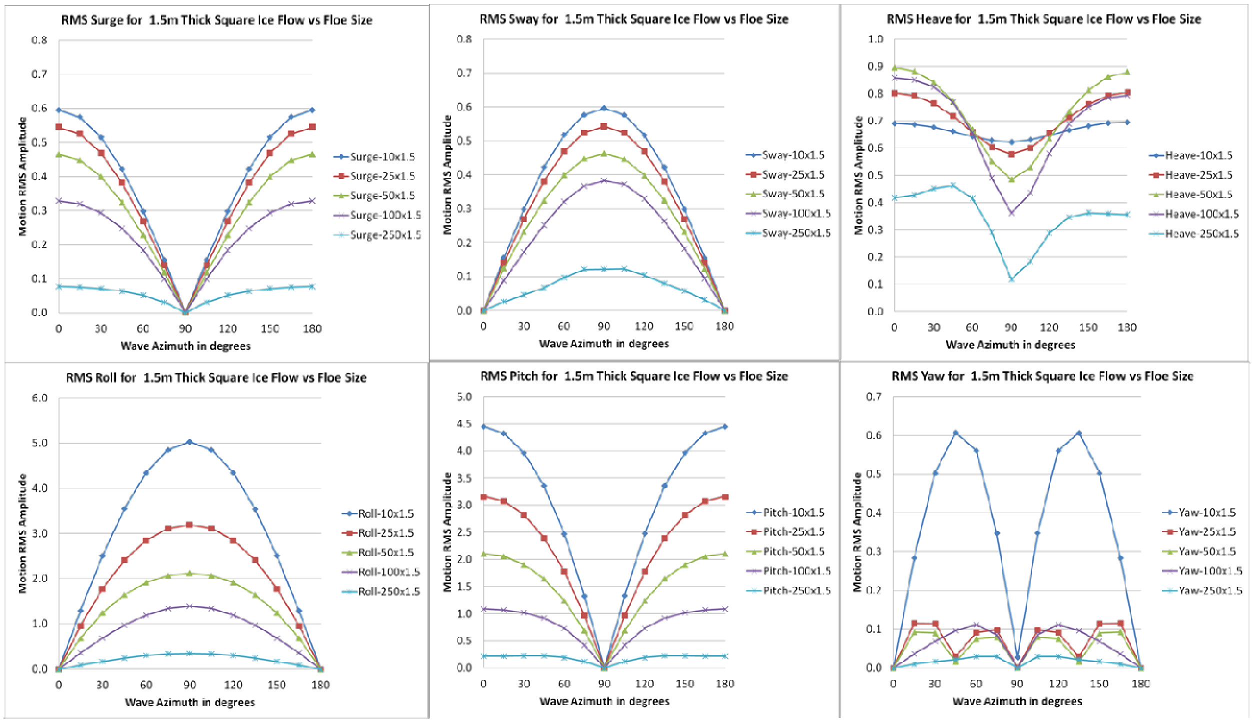


Figure 4: Single Floe Wave Response Motions Variation with Area Extent

Figure 4 shows that there is a significant difference in response to waves depending on the floe size. All of the floes in this table were excited with a Bretschneider spectrum with a 2.5m significant wave height and the NATO 50% modal period of 8.8 seconds.

It is not surprising that for a single modal period of incident waves, the largest heaviest floes move the least. The wave spectra used in all of these cases has a range of period components from 2 to 24 seconds in 0.5 second intervals. Unevenly spaced components offer the advantage of the ability to create longer time series before the pattern repeats, but the even spacing allowed the use of existing data reduction tools which was good enough for this proof of concept work.

The frequency dependent phase information is not included in the integration scheme, so these values are not completely correct according to the standard methods. However, they were good enough to show the relative behaviors between floes of different area extents and thickness values.

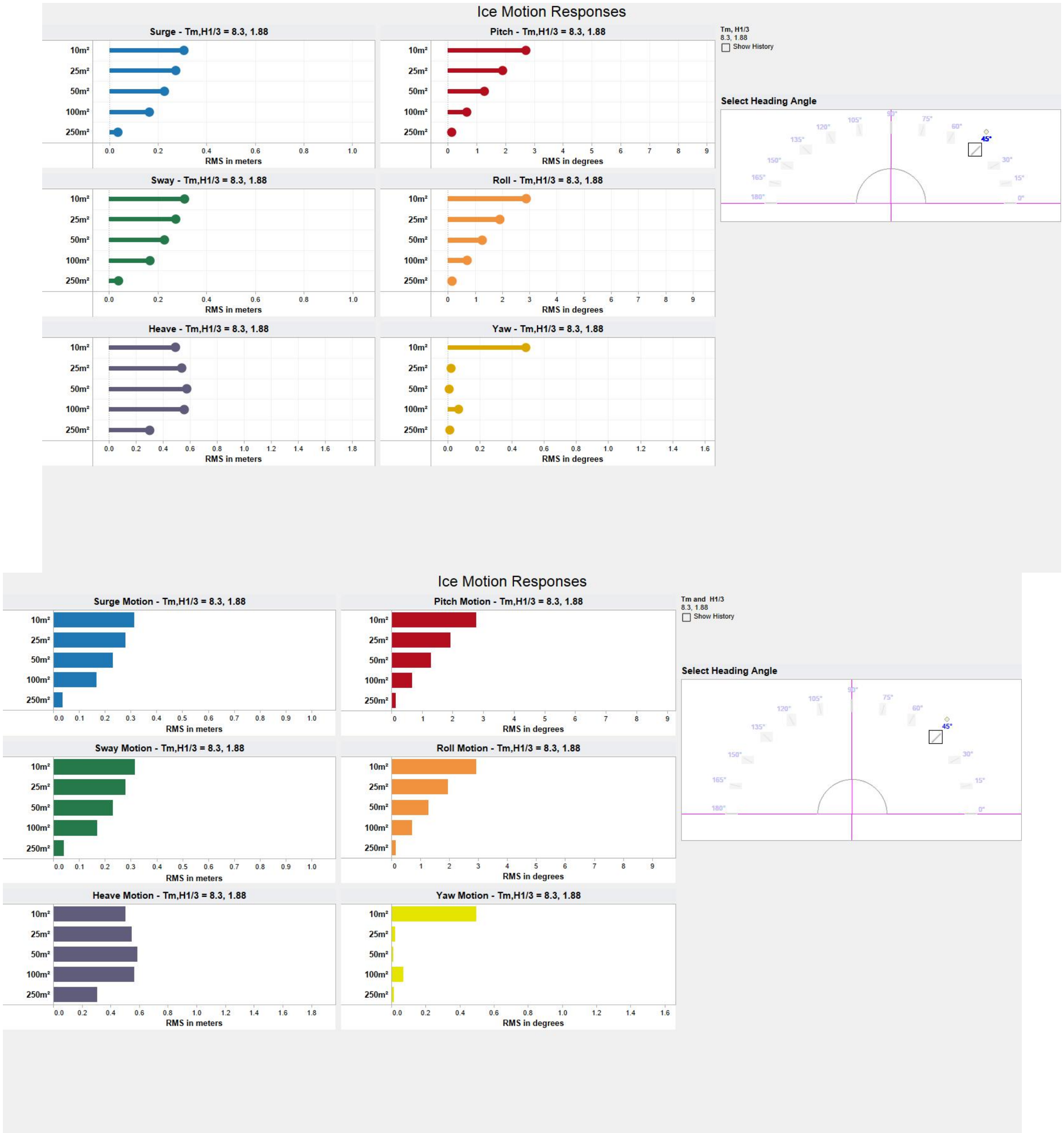


Figure 5: Single Floe Wave Response Motions Variation with Extent Shown in a Tableau Lollipop Graph

Figure 5 shows the same data as in figure 4 expressed in Tableau as a lollipop graph. The Tableau version has a slider and dial that allows the viewer to scan across different lengths of time between wave crests, significant wave heights, and headings, which allows for investigating the effects and interactions of multiple variables. Unfortunately paper publishing technology does not allow the inclusion of such animations at the current time.

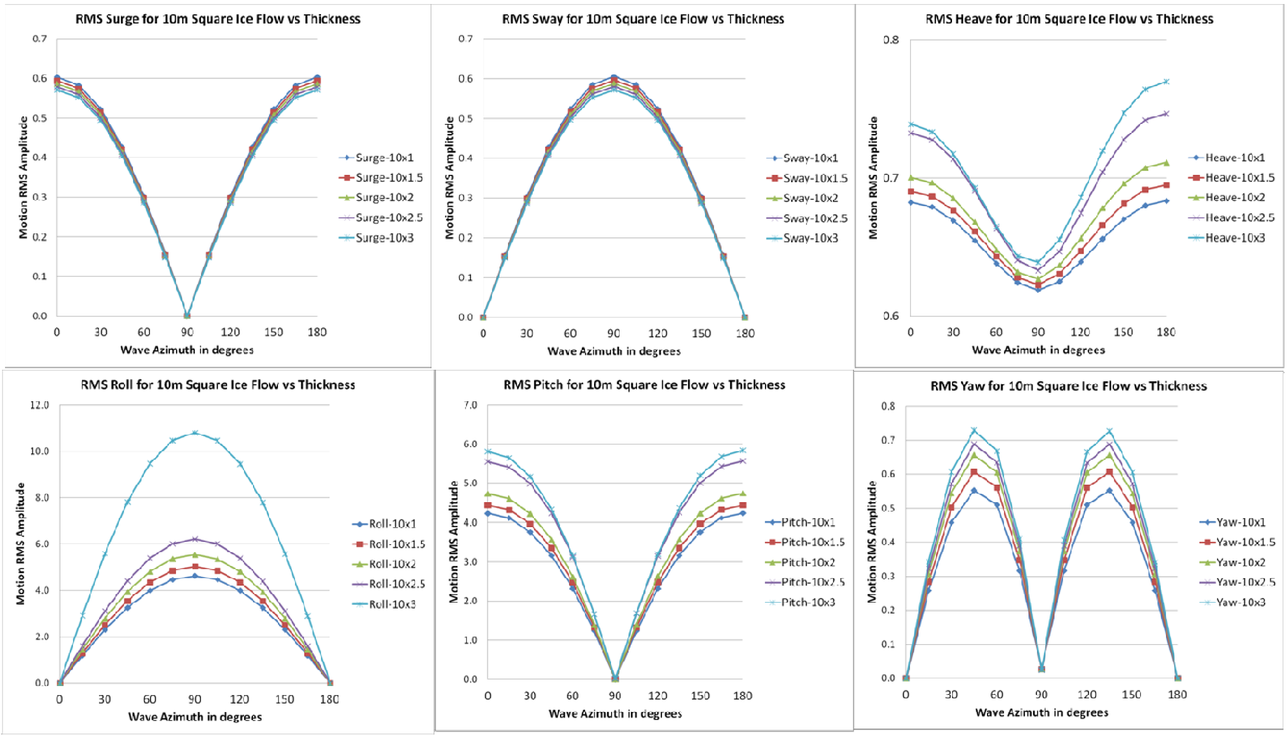


Figure 6: Single Floe Wave Response Motions Variation with Thickness

Figure 6 shows the same comparison type applied across the 5 different thickness values from 1 to 3m thickness for 10m square floes. The motions are much less susceptible to differences in thickness than they are to differences in area extent, which matches what the RAO's showed earlier.

Shear, Bending and Fatigue Modeling of Single Floes

The strength properties of ice floes vary substantially with strong dependencies on the presence of brine pockets, air bubbles, ambient temperature, age of the ice and the micro and macroscopic structure of the local sea ice floe or sheet. Timco & Weeks (2010)

Table 3: Range of Ice Strength Properties Applied to a Model Flow

	Min	Max	Mean		min	max	mean	
Tensile Strength	0.2	0.8	0.50	mPa	29.0	116.0	72.5	psi
Compression Strength	0.4	12	6.20	mPa	58.0	1740.5	899.2	psi
Flexural Strength	100	150	125	kPa	14.5	21.8	18.1	psi
Shear Strength	650	2300	1475	kPa	94.3	333.6	213.9	psi
Youngs Modulus	1	10	5.5	Gpa	1.450E-05	1.450E-06	7.977E-05	psi

		Width	Thickness	Area	c	I	Critical Bending
	m	m	m	m^2	m	m^4	Moment
Floe Length	100.00						kPa
Floe Diagonal Length	141.42						(mean tensile)
1/4 Diagonal Length	35.36	70.71	1.50	106.07	0.38	19.89	1.45841E-11
1/3 Diagonal Length	47.14	94.28	1.50	141.42	0.38	26.52	1.94454E-11
1/2 Diagonal Length	70.71	141.42	1.50	212.13	0.38	39.77	2.91682E-11

Table 3 shows the range of various strength properties found by Timco & Weeks (ibid), in the top panel and then in the lower panel, one way in which those might be applied to a 100m square by 1.5m thick floe with the waves coming from one diagonal corner.

This methodology can be used to estimate the wave heights and modal periods required to break up a specific size of ice flow.

In general, multi-year ice is stronger than first year ice, and summer ice that is melting is much weaker than midwinter ice when the temperatures are at their lowest and the ice is hardest. As sea ice is formed, brine pockets are formed and these gradually creep down through the floe and may eventually ventilate back into the sea at the bottom of the ice. These leave an empty air pocket behind that is both a volumetric void that cannot bear a load and a stress concentration that can serve as a failure initiation site in an otherwise brittle material. These air gaps occur first at the upper parts of the flow, whereas the brine pockets are incompressible similar to water.

The anisotropic material properties of sea ice with the brine and ex-brine cavities will probably have some of the same material fatigue behaviors found with cast irons with their carbon matrix inclusions or wrought irons with their slag inclusion layers.

Note that glacial ice found in icebergs can have much different properties than these values given for sea and freshwater ice. Glacial ice is multi-year ice that was deposited on top of previous ice and not formed by cooling of seawater, so the brine pockets are absent. Glacial ice has been compacted under pressure from the weight of the overburden for many years.

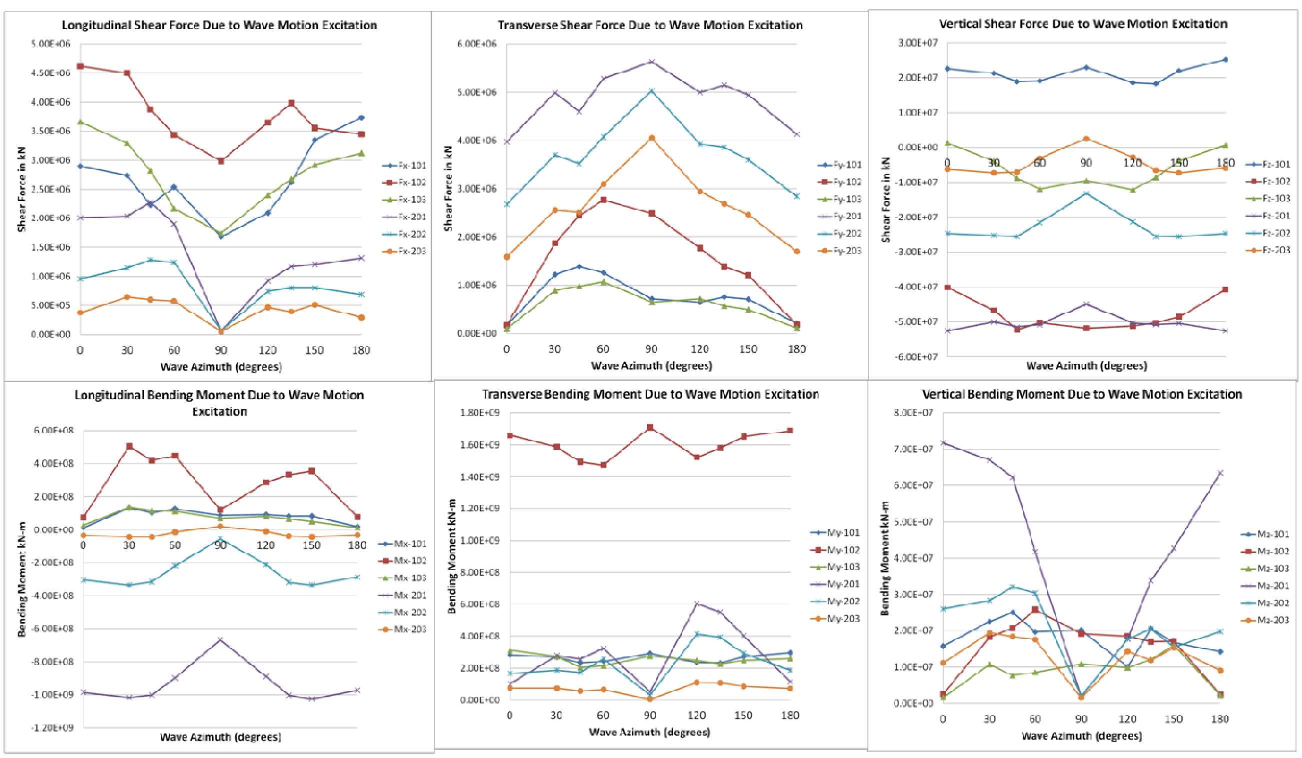


Figure 7: Shear & Bending of 100m^2 Floe due to Wave Excitation

Figure 7 shows the maximum 3 axis shear and 3 axis bending moments of a 100m square ice floe 1.5m thick when excited by a 2.5m significant wave height and an 8.8 second modal period Bretschneider spectrum. This data was created in the WASIM non linear model with 200 non evenly spaced period components for a 2400 second (40 Minute) run (282 wave encounters) at each azimuth direction plotted. The use of non evenly spaced spectral components increases the length of time before the time series begins to repeat. The repeat interval in this case is much greater than the 40 minutes simulated.

The significance of this graphic is to show the types of data that can be extracted from the model, and some of the variability involved in the outputs as a function of where the cut plane is located, the direction of the stress, and the wave properties that caused the loads.

Just like metals, ice is susceptible to fatigue loading, which can be extracted from the linear and non-linear models. In general, the non-linear time series results produce more trustworthy results for these low freeboard floes where green water on deck is a common occurrence.

Table 4: Example of Data Run Through a Fatigue Cycle Counter

	Bretschneider											
Speed	Seastate	H/13 (m)	Tm(sec)	Heading	Duration		Y-Z					
kn				deg	sec		Fx-101	Fy-101	Fz-101	Mx-101	My-101	Mz-101
0	4	2.5	8.8	180	2480	>1.0e6	0.0	0.0	176.0	0.0	176.0	3.0
			Head Seas			>5.0e5 & <=1.0e6	165.0	0.0	0.0	89.0	0.0	133.0
	100m square floe					>1.0e5 & <=5.0e5	11.0	1.0	0.0	36.0	0.0	9.0
	Realization R0					>5.0e4 & <=1.0e5	0.0	27.0	0.0	5.0	0.0	1.0
						>1.0e4 & <=5.0e4	0.0	88.0	0.0	4.0	0.0	4.0
						>0 & <=1.0e4	0.0	39.0	0.0	7.0	0.0	2.0
						<=0 & > -1.0e4	0.0	21.0	0.0	6.0	0.0	3.0
						<= -1.0e4 & > -5e4	0.0	0.0	0.0	5.0	0.0	0.0
						<=-5e4 & >-1.0e5	0.0	0.0	0.0	24.0	0.0	10.0
						<=-1.0e5 & >-5.0e5	0.0	0.0	0.0	0.0	0.0	0.0
						<=-5e5 & >-1e6	0.0	0.0	0.0	0.0	0.0	11.0
						<=-1.0e6	0.0	0.0	0.0	0.0	0.0	0.0

Table 4 was created by running the non-linear time series data through a peak counter in Matlab. The size and the shape of the bins must be customized in this to fit the data being analyzed. From there with enough runs, an S/N curve can be created that can be compared to an S/N curve for the ice. Unfortunately, no such standard S/N curve for sea-ice that is applicable to a generic floe exists. The extreme sensitivity of the other mechanical properties of sea ice to temperature, age, brine pockets etc., suggests that no such generally applicable curve or family of curves are likely to be created at least to the level where they exist for metals.

Predicting maxima and minima from the linear theory RMS using standard statistical methods is dodgy at best, because of the assumptions that underlie the simplistic methodology. Text books assume that ocean waves are Gaussian and that the peaks follow a Rayleigh distribution, which is true for small waves and responses. However, real ocean waves acting on something low lying like an ice floe, will partially wash over the top and splash, causing the floes to flex significantly, crash into one another, and interact with slush or thin ice in the leads between floes. All of this, along with other non-linearitiess in the waves and their interaction with winds, currents, and water column stratification; bottom interactions; and the radiation, reflections, and diffraction off of other floes, quickly make text book assumptions fail a reality check.

The behavior is a chaotic superposition of multiple non-linear inputs and non-linear responses, so any assumption that it follows a generic statistical form remains to be proven from multiple real world data sets before it can safely be taken for granted.

Single Floe Motions in Linear vs. Non-Linear Models

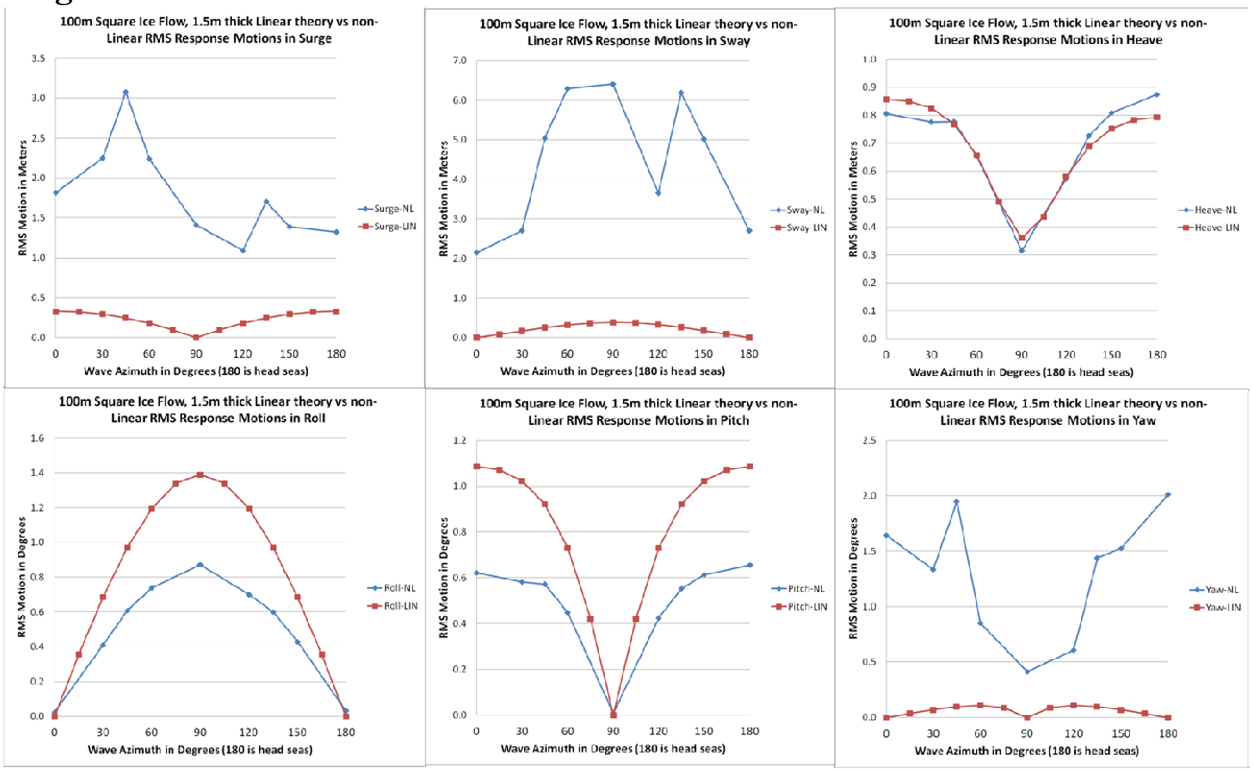


Figure 8: RMS Responses to 2.5m Wave Spectra from Linear and Non-Linear Modeling Programs

Figure 8 shows the linear and non-linear results for the same ice floe panelization and same sea conditions. The Surge, Sway and Yaw degrees of freedom do not have a gravity restoring force like Heave, Roll and Pitch do, so those results are always a bit scattershot in every seakeeping program the authors have ever used including Visual SMP, Shipmo, VERES, FD_waveload and others. The heave, roll and pitch do have a restoring force and are generally better behaved. In figure 8 the heave tracks very well. The linear results for the roll and pitch show that the linear results greatly exceed the non-linear results. The linear modeling does not include the effect of waves partially washing over the top of the flow, which the non-linear WASIM model includes. Unfortunately, no real world or model scale results are available to validate or verify these results. The gross patterns in the results are probably valid, but the accuracy / exact magnitudes of the responses must not be overstated.

Table 5: Sensitivity of Non-Linear Results

Heading	Encounters	282					
Angle		Surge-NL	Sway-NL	Heave-NL	Roll-NL	Pitch-NL	Yaw-NL
180	Max/RMS	3.09	2.84	2.62	4.89	3.63	1.99
150	Max/RMS	2.69	2.66	2.51	3.64	3.29	3.60
135	Max/RMS	4.33	2.90	2.58	3.85	3.55	3.25
120	Max/RMS	2.13	3.00	2.39	3.75	3.68	2.81
90	Max/RMS	3.41	2.43	2.04	4.42	8.14	4.12
60	Max/RMS	2.65	2.39	3.61	4.08	4.77	2.56
45	Max/RMS	2.84	3.45	3.51	3.72	4.48	2.54
30	Max/RMS	2.87	3.56	4.22	3.76	4.88	2.76
0	Max/RMS	3.19	3.39	4.68	5.38	5.35	2.33

Table 5 shows the maximum divided by the RMS in each time series for each heading and degree of freedom from the non-linear WASIM sea state 4 simulations.

Linear theory and standard equations by Ochi tell us that the maximum value in a given number of waves will be a constant multiplied by the RMS where the constant is mostly a function of the number of waves encountered. Ochi (2003)

If that were true, then the maximum value divided by the RMS should be constant for each degree of freedom in each time series. This is clearly not the case. For 282 encounters, this is 3.36 times the RMS. The majority of the RMS multipliers in table 5 are significantly different than this constant 3.36 value.

Table 5 is an effective measure of all of the various forms of non-linearity acting together, and it shows that the linear assumptions are highly suspect for determining realistic maxima.

Modeling of Multiple Floes and Leads with Radiation and Diffraction

The WADAM model allows the user to put up to 15 different bodies into a pattern on the water's surface and then calculates the RAOs of each with radiation and diffraction from each of the other bodies. This was exercised for 10m^2 and 100m^2 ice floes in a number of different configurations. The RAO's were run for every 30 degrees around the compass so that waves directed along or across different geometries could be evaluated. Unfortunately, the multi-body formulation does not support the analyses of the shear and bending moment cut planes.

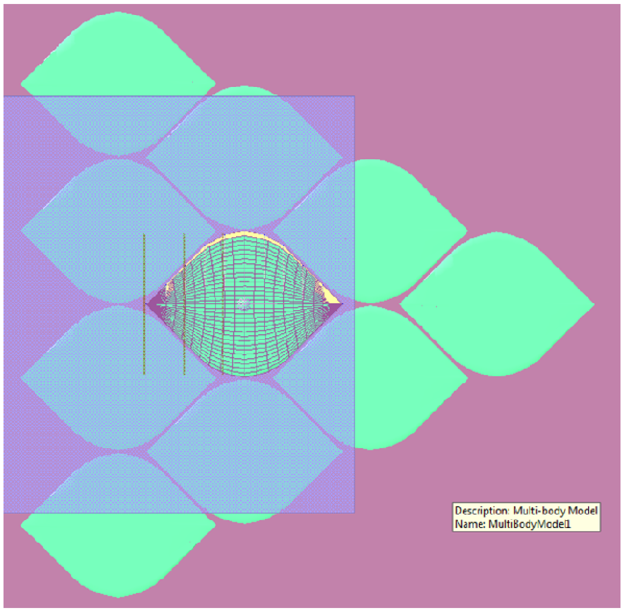
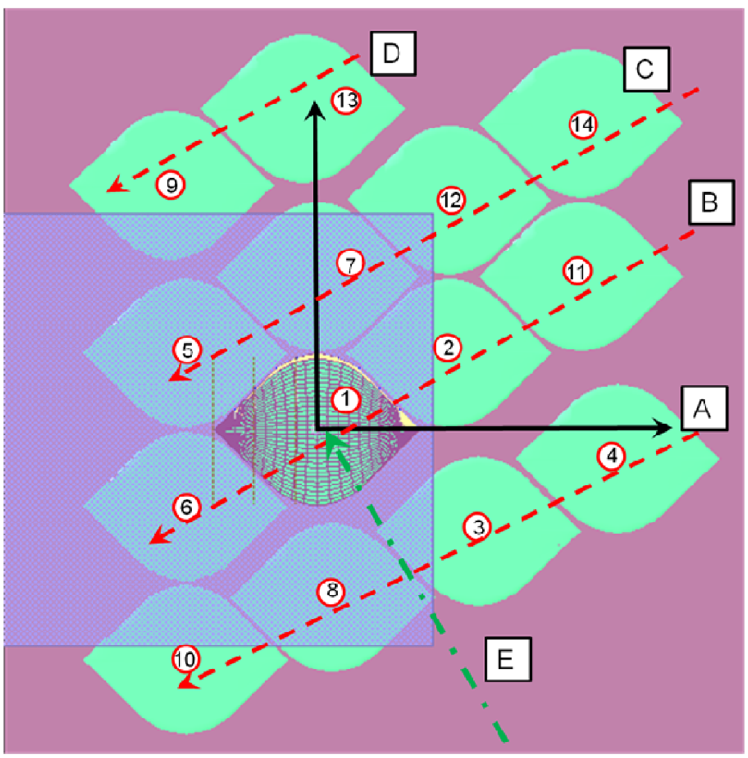


Figure 9: 10 each 10m² floes in a Ten Pin Arrangement



Floe Number	X Centeroid	Y Centeroid
1	0	0
2	91	53
3	111	-70
4	207	-20
5	-91	53
6	-91	-53
7	0	106
8	10	-116
9	-101	169
10	-91	-159
11	182	106
12	91	159
13	-10	222
14	182	212

Figure 10: Transects Along and Across the Leads & Floes

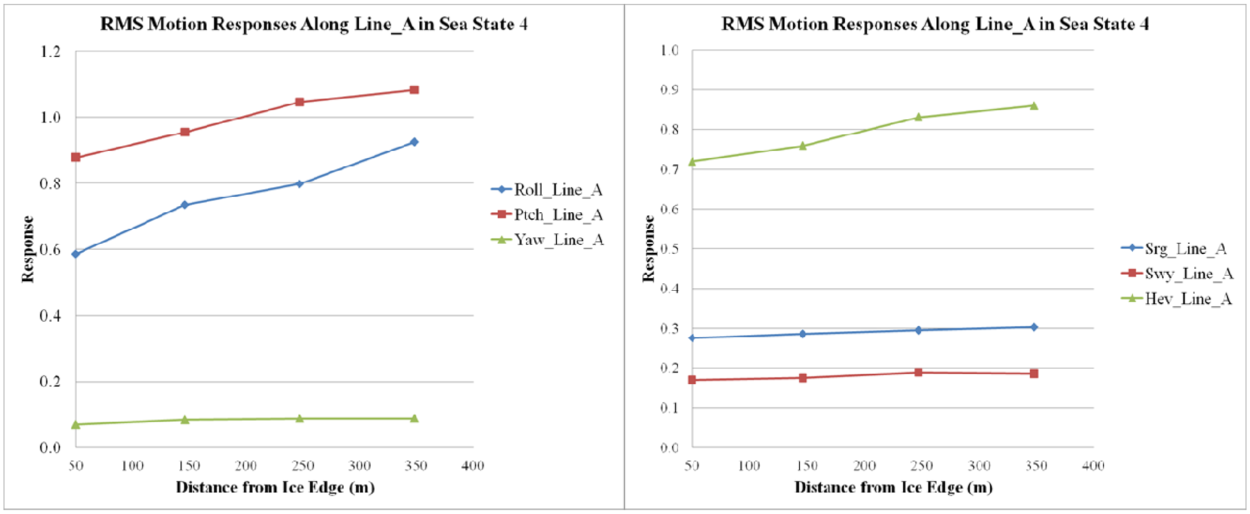


Figure 11: Motions in Sea State 4 vs Distance from the Ice Edge

Figure 11 shows the motions when the RAO's representing transect A in the ice floe arrangement in figure 10, are excited with a 2.5m H1/3 at an 8.8 second modal period Bretschneider spectrum. The heave, roll and pitch motions show a marked attenuation with distance inside the ice edge, which is reasonable and expected. A simple curve fit to each of these could be extrapolated to the Y intercept to estimate the distance from the ice edge for that wave train to be attenuated to zero in a long series of 100m square floes 1.5m thick. .

The earlier results suggest that this is strongly a function of wave component period and floe size. A systematic evaluation of the attenuation in from the ice edge is well within the capabilities of the software, but is beyond the scope of the current studies.

Such a characterization to include different sizes and thickness of ice floes and even different water depths is easily within the capabilities of this software. Interrogating these RAO's for other wave spectra is fairly trivial, and an extensive set of data already exists.

However the verification and validity of those estimates would require that there was empirical data to calibrate it against. To the authors' knowledge, such a data set has never been recorded.

Additional questions of the investigation include: Would an alternative arrangement of the 15 floes proved better information? Would a specific thickness gradient from ice edge inward be more representative? In principle, any floe shape that will close in the panel model can be investigated. Are there additional studies worth pursuing in the absence of a validation data set?

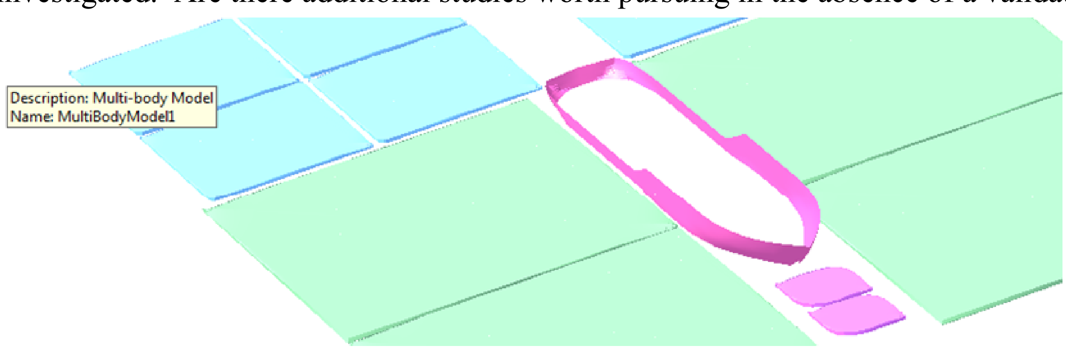


Figure 12: Icebreaker Model in Simulated Floes in WADAM

This study is limited to an evaluation of the software's capabilities and was not focused on providing scientific results.

Figure 12 shows that a range of different objects can be modeled in the WADAM code if the panel mesh can be made to close for all of them.

Mixed Theory Modeling in OrcaFlex

The OrcaFlex program allows the user to model winds, waves and currents acting simultaneously, or in any combination, on a wide range of different objects underwater and on the surface of the ocean.

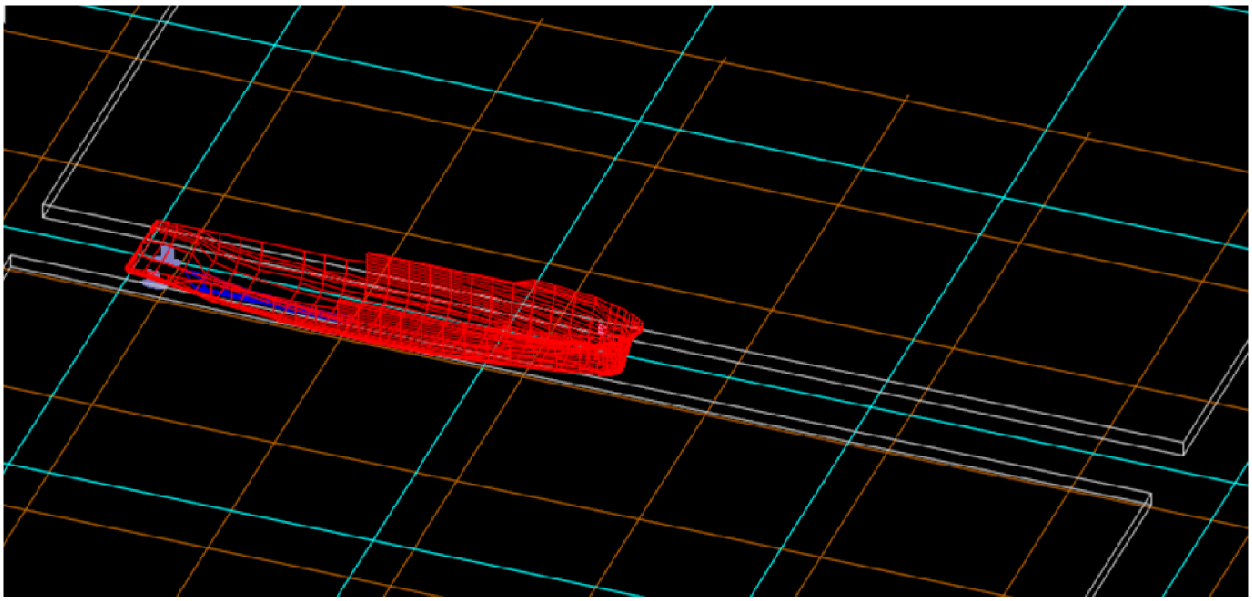


Figure 13: OrcaFlex Model of Candidate ABS Baltic Rules 1A Research Vessel in Pack Ice

The models illustrated in figures 12 through 14 represent works in progress. In the OrcaFlex model, either non-linear time series motions or several types of RAO's can be imported.

The force and moment Haskind RAO's with frequency dependent added mass and damping may be preferable to the simpler motions RAOs because the F&M RAOs allow the inclusion of other forcing into the computation of the vessels motions.

In order for the model in figures 13 and 14 to show the ship actually breaking ice, a number of setup steps are necessary that are not illustrated in these simplified graphics.

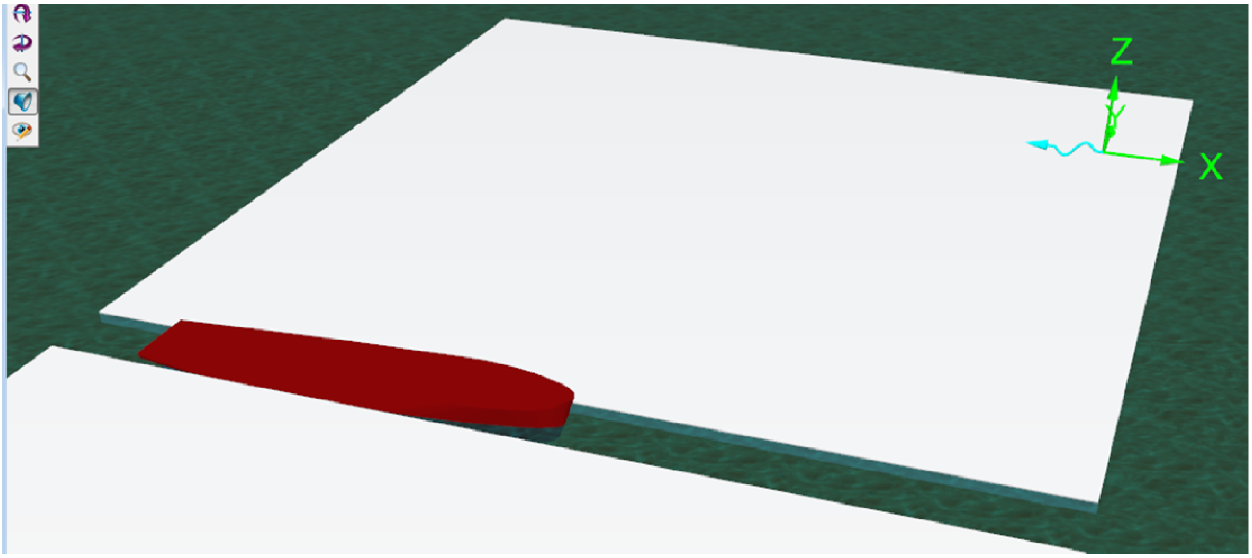


Figure 14: Same as Figure 13 but with Shaded Graphics instead of Wire Frame Graphics

The additional setup steps include:

- The floes flanking the ship can be rigidly fixed in place or they can be setup as vessels with their own RAO's to respond to waves and ship forcing.
- The vessel shape must be fitted out with internal shapes that have realistic elastic and damping properties, below the waterline and as far above it as ice impacts are expected to occur.
- Brash ice chunks in the wake and ahead of the ship must be built up as buoys or vessels and co-located with internal elastic bodies with the desired mechanical properties, to allow modeling of the body to body collisions.
- A network of links between the brash ice floes can be set up ahead of the ship and set to break when the force exceeds a user designed maximum loading condition. That way as the vessel proceeds either forward or aft, the brash ice can be made to break up and interact with the hull, appendages, propellers and other ice floes.
- The appendages were attached to the parent hull form as separate 6DOF buoys. This then allows the hydrodynamic interactions and body on body collision forces and moments to be modeled and the data extracted independent of the parent hull.
    - OrcaFlex has the capability to model the interaction of propeller blades with ice chunks at some level. The fidelity of the results would depend on how the setup was handled and limitations of the software that have not been researched at this time.

Time series results in an excel spreadsheet format can be easily output for any and all parameters of interest. Video footage of the graphical simulation can be created that will play in any video player program.

Discussion

This broad study began with the question of what aspects of ice floe motions and ice breaking can be handled using existing, well validated, commercial off the shelf (COTS) software. The systematic exploration described in this paper explores the overall modeling space at a minimal level. The range of COTS software packages includes many others beyond those that were on hand to support this effort. The sizes, shapes and mechanical properties of the ice floes were represented by 2 crossings through the broader parametric space.

The results produced seem reasonable within the known limitations of the software.

- Larger heavier vessels move less in waves than smaller lighter vessels and the ice floes show a similar behavior.
- For a symmetrical square shape there is not much difference between the pitch and roll behavior when the relative angle behavior is accounted for by shifting the pattern 90 degrees in azimuth.
- For the heave degree of freedom, the ratio of response to input wave height goes to one at long wave periods which makes physical sense.

The absolute and detailed accuracy of any of the results would require available field data, which the software could try to replicate, and at this time that data is not available.

For modeling a ship breaking ice, there is a limited amount of data available in the technical literature that could be used in a verification effort.

Future Possible Modeling Efforts Available Using This Software.

In many ways, this broad survey has only touched the surface of what the various existing software packages can do with respect of ice modeling and ice breaking.

So far the ice floes have been treated as a rigid body. The WASIM and WADAM packages have the ability to integrate with a commercial finite element software package where it is probably possible to allow larger floes to dynamically deflect. That would require a bit of a leap of faith in that the material properties of the ice would have to be treated as at least piecewise isotropic. When these codes are used with a detailed ship model the local strength and stiffness, which vary with the construction details, are part of the model and so it would be for the ice. The wide range of ice strength parameters available would suggest a variation of parameters approach.

A model of wave damping by ice flow thickness and distance in from the ice edge as a function of wave modal period and water depth would be relatively straight forward to achieve, but data for verification would greatly benefit the validity of the outcome.

The OrcaFlex model offers many different possibilities.

MacAyeal et al 2006 describes the breakup of an enormous ice sheet off of Antarctica due to waves that originated from a storm in the Gulf of Alaska, half a planet away.

OrcaFlex objects can be joined by hinge joints with tension and compression links represented as a force vs displacement and damping vs velocity curve fit. A network of these could be used to model the flexure of large ice sheets due to waves.

Many more than 15 objects of arbitrary shape can be placed in OrcaFlex with realistic buoyancy and freeboard and with body on body elastic collision modeling enabled.

- This could be used with the WADAM RAO's or data from other programs to show green water washing across the top of ice floes.
- The body on body collisions as waves or icebreaker or wind or current induced floe motions cause them to grind or strike together, can be modeled and the forces and moments can be easily extracted from the resulting non-linear time series.
- OrcaFlex can model one ice floe riding up over the top of another. The interbody friction coefficients can be adjusted to make them slip back off or stick there.
- The act of the Titanic or other vessel striking due to any kind of a blow on an iceberg are only limited by the lack of geometry and mechanical property information for the iceberg.
- OrcaFlex does not have a native capability to model short crested waves, but it can be done by entering the wave components one by one, each with their properties of amplitude, spectral period and direction of travel. WASIM allows long crested or cosine spreading to be modeled.
- OrcaFlex and WASIM both allow the superposition of multiple wave trains to simulate a sea and a swell coming from different directions and interacting with the object of the study. Both can also handle an Ochi-Hubble 6 parameter spectrum as well as other standard spectral forms. NOAA/NDBC wave buoy spectra have been successfully modeled in OrcaFlex on past projects to represent the spectrum present at a specific place and time as recorded by the buoy data.
- The motions of ice floes due to wind forcing can be modeled at least to the extent that a realistic input of boundary layer physics, wind drag on the ice upper surface and motion / current induced drag on the bottom of the ice can be developed.
    - Information on the drag coefficients for large scale ice sheets due to wind are unknown to the authors, but the Shoenherr line for a flat plate can probably provide some reasonable guidance. Lewis et al (1988)
    - This can be used with the aforementioned hinge joints and body on body contact to investigate the formation of pressure ridges at least to some degree.
- The OrcaFlex software allows the user to put in bottom contours to some level and include some level of sediment properties.
    - It is probably possible to model waves acting on shorefast ice, or the shear and impact of moving ice acting on shorefast ice.
    - It is possible to show the keel of an iceberg dragging on the bottom.
    - It may be possible to show the effect of rising and falling tides on shorefast ice and near shore or shallow water ice.

Closing Comments

The initial question was; "Can COTS software used in the ship design and offshore energy industry be used to effectively model ice on ice and ice on ship interactions?"

The answer as developed in this paper is a resounding YES.

The software discussed can model fresh or salt water with a trivial change in the setup parameters so that was not discussed in any detail.

There are a vast number of studies that could be conducted from this data pond, and from this software at some level of accuracy to form a basis of further deeper investigations. The authors are willing to share the data developed so far that does not contain ship information with other investigators and to provide guidance to students who might wish to use this data as part of undergraduate or graduate level thesis projects.

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Appendix 1: Descriptions of codes utilized.

"WAve SIMulation (WASIM) solves the fully 3-dimensional radiation / diffraction problem by Rankine Panel Method" (DNV Software 2006). The non linear model includes integration of the Hydrostatic and Froude-Krylov pressure over the exact wetted surface, the Bernoulli equation including quadratic terms, quadratic roll damping and exact treatment of the rotation angles in inertia and gravity terms. (DNV Software 2006).

WASIM is a 2-1/2 D panel code, based upon the MIT SWAN 2 Code, that allows both non-linear time series creation as well as the creation of Response Amplitude Operators (RAOs) based upon a Fast Fourier Transform (FFT) of a group of linear or non-linear time series runs, with or without forward speed. In the non-linear time series runs, WASIM is capable to modeling 6 degree of freedom shear force and bending moments at user selected slices through the hull geometry. It also allows the modeling of semi-submerged and submerged elements and the calculation of green water on deck as well as some wave slam and wave slap forces through post processing. The version of WASIM available is limited to a single hull being modeled at one time.

WADAM multi-body is a Linear panel code based on the MIT WAMIT code that allows the calculation of RAOs at zero speed for up to 15 different bodies in user selected proximity at zero speed. In single body mode WADAM can also calculate RAOs for the shear and bending forces at user selected locations similar to WASIM. WADAM also outputs RAOs that develop the forces and moments on the body as a whole based upon the wave motions inputs, and the frequency dependent added mass and damping matrices.

OrcaFlex is a blended graphical modeling code that models the behavior of a wide range of things at the sea surface, submerged in the water column and at the sea bottom interface to a wide range of wind, current and wave forcing scenarios.

To quote from the manual, "OrcaFlex is a fully 3D non-linear time domain finite element program capable of dealing with arbitrarily large deflections of the flexible from the initial configuration. A lumped mass element is used which greatly simplifies the mathematical formulation and allows quick and efficient development of the program to include additional force terms and constraints on the system in response to new engineering requirements."

OrcaFlex does not currently have an organic capability to calculate vessel motions from geometry and loading but has at least three different ways of modeling them with the help of other software. OrcaFlex can model motions due to waves and object to object interactions as follows:

- Using a user selected wave model and user supplied displacement RAOs
- Using a user selected wave model and user selected force and moment RAOs and added mass and damping matrices.
- User supplied time series of object motion.

Each of the 3 programs has its features and limitations that were investigated to see which of them could best be brought to bear on the problem.