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Capability Analysis of Dynamic Positioning for the Arctic FPSO in ICE

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ABSTRACT

Dynamic positioning (DP), which is widely used in a large range of marine operations nowadays, is a computer-controlled system to automatically maintain a vessel's position and heading by using its own thrusters. To evaluate the capability of DP, the standard method proposed by International Marine Contractors Association (IMCA) is widely used at the early design stage. The capability in open water is normally described as capability plots with respect to maximum thrust or maximum environmental condition by considering the given environmental loads. However, in ice-covered water, the ice load is a dominant factor among the other environmental loads. The ice loads are totally stochastic and vary with many parameters such as ice thickness, ice density, ice drift speed, strength of ice. There are some numerical methods to estimate the ice loads have been proposed and developed.

In this study, the global ice loads for a ship-type Arctic FPSO are calculated for various ice parameters with the software GEM (GPU Event Mechanics), developed by Memorial University. Through the DP capability analysis of the Arctic FPSO from the estimated ice loads, the characteristics of DP performance are examined. By this study, the influence of ice parameters are to be identified, which can be used for the design of the capacity and configuration of thrusters and mooring systems .

Keywords: Dynamic positioning (DP), Arctic FPSO, Capability Analysis, Ice load

INTRODUCTION

For offshore operations, it is very important to keep offshore floater at a desired position with adequate heading, nowadays. Operations such as drilling, production, subsea construction, maintenance, pipe-laying, and shuttle offloading are highly dependent on Dynamic Positioning (DP) systems. Environmental forces such as wind, waves and current, tend to move the floater off from the desire position. DP systems play a role to maintain the floater's position and heading by automatically controlling actuators to make balance between thrusts and environmental forces.

At the design stage, it is necessary to identify the DP operational window where the floater can maintain its position and heading because effective operational risk management depends on DP capability. The DP operational window can be found by the static analysis of DP capability. Given environmental conditions, the capability can be examined by quasi-static method to balance the mean environmental loads with the mean thruster forces. The computations and representations of the DP capability have been standardized by the International Marine Contractors Association (IMCA, 2000). The DP capability is generally described as capability plots in polar coordinates with respect to maximum thrust usage or maximum environmental conditions. Currently the capability plots are widely used for floater design in industries due to the advantages of its simplicity.

In ice-covered water, the ice load is a dominant factor among the other environmental loads. Therefore, it is very important to take into account the ice load in analyzing DP performance. The ice loads induced by the interaction between ice and floater are quite different from the other environmental loads in open water. The ice loads are totally stochastic due to the substantial amount of parameters which define ice material such as thickness, elastic modulus, density, flexural strength, etc. Furthermore, it also varies a wide range of ice features, such as level ice, pack ice, ridges, icebergs, etc. Biao et al (2013) carried out a static ice load-based dynamic positioning (DP) capability analysis of the CIVArctic vessel in level ice condition. Kerkeni et al. (2013) reviewed the applicability of the standard method to DP capability analysis in ice-covered water. They suggested the use of dynamic simulation in time-domain to capture stochastic characteristics of the ice field.

This paper presents the DP capability analysis for a ship-type Arctic FPSO in pack ice condition. For the purpose, the ice loads are calculated for various ice parameters with the software GEM (GPU Event Mechanics), developed by Memorial University. In order to capture the stochastic nature of the ice, a series of numerical towing simulation are carried out. Based on the simulated data, the global ice loads are estimated by a numerical analysis of with respect to vessel heading and ice parameters. The characteristics of DP performance are then examined with the estimated global ice loads. Finally, the influence of ice parameters is identified, which can be used for the design of the capacity and configuration of thrusters and mooring systems of the Arctic FPSO.

DP CAPABILITY ANALYSIS

To ensure a standardization in the production of capability plots, IMCA has presented the specification for DP vessels in order to enable a direct comparison of individual vessel's performances and provide an indication of station keeping ability in a common format (IMCA, 2000).

For DP operations of the floaters, the mathematical model at the center of gravity can be described in the body frame as follows:

$$M\dot{v} = F_{coriolis} + F_{wind} + F_{current} + F_{wave} + F_{thrust}. \tag{1}$$

In DP capability analysis, the above model is simplified as quasi-static problem such that the velocity of a floater equal to zero:

$$0 = F_{wind} + F_{current} + F_{wave} + F_{thrust}. \tag{2}$$

The wind load F_{wind} is expressed at the center of gravity of a floater as follows:

$$\begin{aligned} F_{wx} &= \frac{1}{2}\rho_{air} v_w^2 C_{wx}(\alpha_w) A_{wT}, \\ F_{wy} &= \frac{1}{2}\rho_{air} v_w^2 C_{wy}(\alpha_w) A_{wL}, \\ F_{wn} &= \frac{1}{2}\rho_{air} v_w^2 C_{wn}(\alpha_w) A_{wL} \cdot LBP, \end{aligned} \tag{3}$$

where ρ_{air} is density of air, v_w is wind velocity, C_{wx}, C_{wy} and C_{wn} are wind coefficients, A_{wT} and A_{wL} are transverse and longitudinal wind area of floater, LBP is length between perpendiculars. The values for hull wind coefficients are normally determined by wind tunnel test or CFD calculations.

The current load $F_{current}$ is also expressed at the center of gravity of a floater as follows:

$$\begin{aligned} F_{wx} &= \frac{1}{2}\rho_{water} v_c^2 C_{cx}(\alpha_c) A_{cT}, \\ F_{wy} &= \frac{1}{2}\rho_{water} v_c^2 C_{cy}(\alpha_c) A_{cL}, \\ F_{wn} &= \frac{1}{2}\rho_{water} v_c^2 C_{cn}(\alpha_c) A_{cL} \cdot LBP, \end{aligned} \tag{4}$$

where ρ_{water} is density of water, v_c is current velocity, C_{cx}, C_{cy} and C_{cn} are current coefficients, $\mathrm{A_{cT}}$ and $\mathrm{A_{cL}}$ are transverse and longitudinal wind area of floater. The values for current coefficients are also determined by wind tunnel test or CFD calculations.

The wave load F_{wave} is divided into first and second order term. The first order term is described by vertically oscillating zero mean loads. The second term is described by a low frequency load. In the capability analysis, the first order term normally is not taken into account because the DP control systems filter out the first order motion and only respond to the mean wave drift part among the second order term. The wave load F_{wave} is then expressed as follows:

$$F_{\text{wave}} = 2\int_0^{\infty} S_\zeta(\omega) P(\omega,\omega)\, d\omega, \tag{5}$$

where S_ζ is a wave spectrum such as Pierson-Moskvitz or JONSWAP spectrum, and P is a second order response amplitude operator, which can be computed from the potential-based code such as WAMIT, WADAM, etc.

The thrust load F_{thrust} is a total force delivered from all the actuators of a floater such as tunnel thruster, azimuth thruster or propellers with rudders. The steady-state thrust by an actuator can be expressed as

$$F_{thrust} = k_T \rho n^2 D^4. \tag{6}$$

The power consumption as function of the amount of generated thrust F_{thrust} of an actuator, is typically defined by the non-linear relation:

$$P = (P_{max} - P_{min}) \cdot \left(\frac{F_{thrust}}{F_{thrust}^{max}}\right)^{\eta} + P_{min}, \tag{7}$$

where the parameters P_{max}, P_{min} and η are dependent on actuators, where η is typically the value between 1.3 and 1.7.

If the equation (2) can be solved under inequality constraints of power and limitation of the thrust, the floater is then considered to be capable of maintaining the desired position and heading given the environmental conditions. The DP capability plot can be determined after solving the equation (2) with aforementioned constraints for all headings with a certain heading interval. A sample DP capability plot is shown in the figure 1.

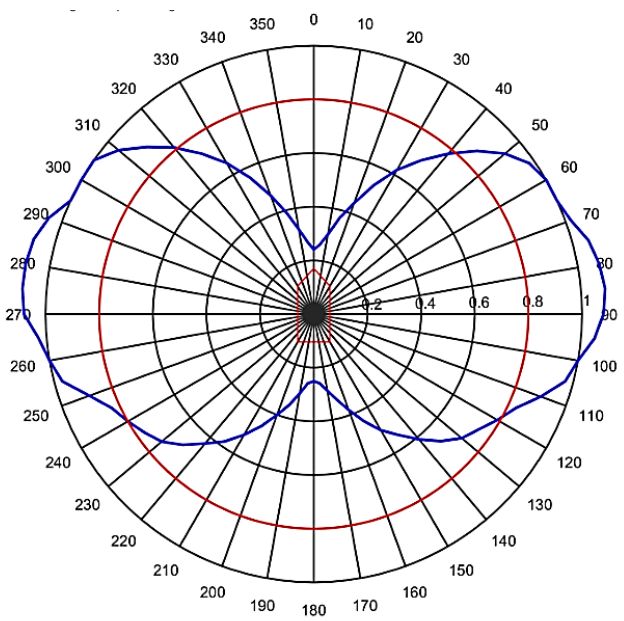

Figure 1. Example of a DP capability plot with respect to maximum thrust usage

ARCTIC FPSO

An Arctic FPSO considered in this study is designed by Samsung Heavy Industries (SHI). This conceptual vessel was designed for a joint collaboration project between KRISO and universities for an initial design of the Arctic FPSO for the government funded project in Korea, started in 2016. Hydrodynamic analysis and a series of experiments will be performed to enhance the way to evaluate the performance of ice capability of an Arctic FPSO .

The Arctic FPSO is 250m long, 50 m breadth and 28 degree as the angle of waterline entrance to have ice capability. The vessel has a turret mooring system, which is integrated into the FPSO's hull, to reduce the ice load on the vessel by ice-vaning to the dominant

environment. In the plan view, the vessel's waterline is a polygon as shown in Figure 2. The vessel has a sloped bow section to ensure ice-going capability by reducing the required ice-breaking loads. This is mainly because the bow area experiences the highest loads, while the other of the hull will generally experience the low loads in ice-breaking. The vessel has also an ice skirt to prevent the ice from going under the bottom of the hull. Furthermore, the hull form of the vessel is designed to improve production efficiency in the ship-yard. Figure 3 shows the 3D shape of the vessel.

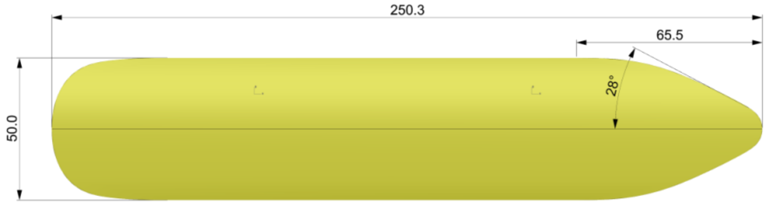

Figure 2. Waterline of the Arctic FPSO

Figure 3. 3D shape of the Arctic FPSO

ICE LOAD ESTIMATION

Ice load estimation on a vessel is very challenging topic. Three different approaches are commonly used for estimating global ice load: i) empirical and statistical models, ii) ice basin tests, and iii) numerical simulations based on physical model. In this paper, the numerical simulator GEM (GPU Event Mechanics) developed by Memorical University (Daley, 2014a and 2014b) is chosen to obtain ice loads in pack ice condition.

The main feature of the GEM is to simulate ice-floater collision and assess global ice loads on the hull operating in pack ice. The GEM can generate ice field that contains hundreds of discrete ice floes. A floater is then modeled to be navigated through the generated ice field. In the simulation, not only ship-ice collision is modeled, but also every ice-ice interaction is modeled. During the simulation, ship-ice collision event is logged and is used later for statistical post-processing. An example of simulation is shown in Figure 4.

For estimating ice loads on the ship-type Arctic FPSO, a series of ice-towing simulations has been carried out to capture stochastic nature of the ice field with some varying parameters of ice thickness, ice density, ice drift speed, crushing strength of ice. The ice represents more than 8/10th ice cover with a constant thickness. During simulation, the Arctic FPSO was towed at varying speeds with fixed heading angles. In the simulations, there were lots of recorded ship-ice collisions, which are used for the basis of the analysis presented. The estimated ice loads are calibrated by multiplying it by a correction factor to reflect the level of ice loads that was measured in model tests with similar size of a vessel.

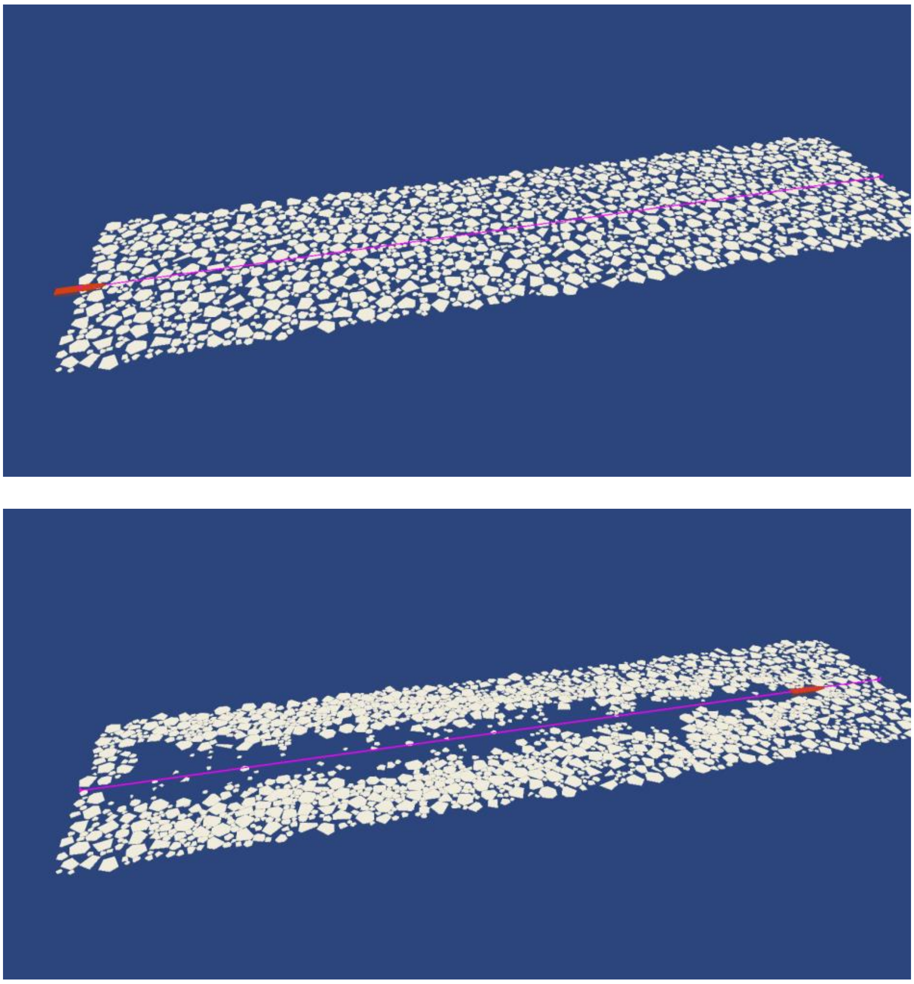

Figure 4. Ice-towing simulations through GEM

Table 1 shows the 60 individual runs that form the data for the capability analysis. A summary of the simulation parameters and results are given. An example of the simulated ice loads is shown in Figure 5. It can be found that the ice loads are gradually increases when the vessel moves through the ice field. This is because the compaction of the ice field leads to gradual force increase. In addition, it can be also found that the signals of the ice loads are significantly oscillated because of the ship-ice interaction, i.e., ice collisions. For DP capability analysis, the data was averaged with a certain period after the data reaching static interval. The list of simulation runs are summarized with summary of the results in Table 1. The results are also presented in Figures 6 - 9.

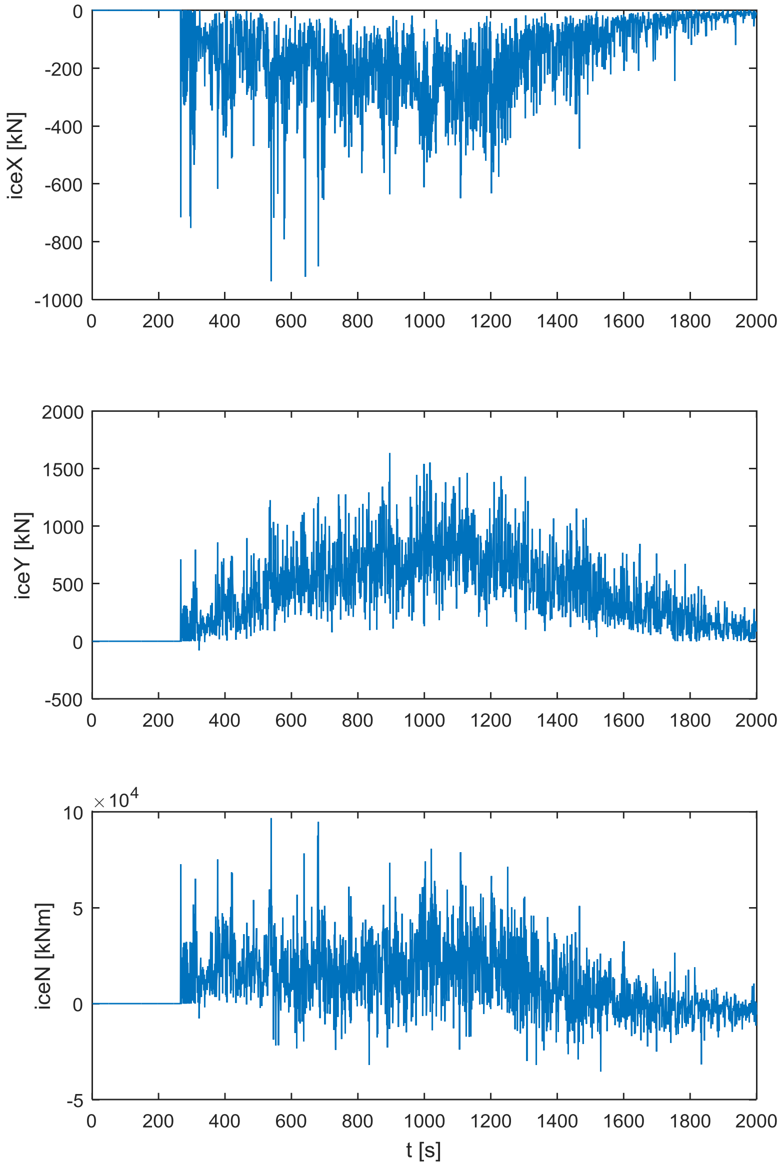

Figure 5. Example of the simulated ice loads

(Run 22: Ice thickness 1 m, Density 850 kg/m^3, Heading 30 deg, Drift speed 0.5 m/s)

Table 1. List of simulation runs with summary of result values

Run No.	Ice thickness	Density	Drift speed	Crushing strength	Heading	Ice Load					
						Xmean	Xmin	Ymean	Ymax	Nmean	Nmax
	[m]	[kg/m^3]	[m/s]	[Mpa]	[deg]	[kN]	[kN]	[kN]	[kN]	[kNm]	[kNm]
1	1	900	1	2	0	-200	-981	-5	432	-346	42,415
2	1	900	1	2	10	-201	-931	132	886	5,093	95,920
3	1	900	1	2	20	-227	-784	456	1,407	17,784	70,885
4	1	900	1	2	30	-263	-939	752	1,854	21,016	75,565
5	1	900	1	2	40	-319	-865	1,200	2,701	26,583	112,510
6	1	900	1	2	50	-354	-874	1,563	3,452	25,292	100,425
7	2	900	1	2	0	-290	-1,830	18	680	1,769	66,045
8	2	900	1	2	10	-314	-1,603	222	1,064	12,523	81,385
9	2	900	1	2	20	-353	-1,702	660	2,040	25,292	156,470
10	2	900	1	2	30	-378	-1,565	1,132	2,745	29,364	133,670
11	2	900	1	2	40	-481	-1,195	1,744	3,478	41,265	169,145
12	2	900	1	2	50	-524	-1,294	2,326	5,149	40,962	197,040
13	2	900	1	2	0	-407	-1,972	-17	1,602	-1,068	180,010
14	2	900	1	2	10	-377	-1,359	335	1,358	16,732	107,625
15	2	900	1	2	20	-467	-2,176	851	2,410	33,955	169,075
16	2	900	1	2	30	-545	-1,456	1,545	3,137	43,683	163,315
17	2	900	1	2	40	-618	-1,753	2,275	5,942	55,900	233,205
18	2	900	1	2	50	-659	-1,864	3,014	6,541	51,835	247,770
19	1	850	1	2	0	-186	-810	-3	353	-216	37,383
20	1	850	1	2	10	-190	-934	128	599	5,942	60,900
21	1	850	1	2	20	-231	-1,255	423	1,061	15,198	73,800
22	1	850	1	2	30	-247	-650	745	1,635	20,468	80,715
23	1	850	1	2	40	-316	-941	1,165	2,730	26,292	103,845
24	1	850	1	2	50	-344	-959	1,500	2,919	27,153	131,450
25	1	950	1	2	0	-196	-883	-9	504	-692	45,344
26	1	950	1	2	10	-229	-1,165	169	742	9,308	72,850
27	1	950	1	2	20	-247	-1,201	486	1,327	17,023	74,845
28	1	950	1	2	30	-279	-777	861	2,032	24,629	97,580
29	1	950	1	2	40	-330	-866	1,285	2,598	26,796	120,065
30	1	950	1	2	50	-364	-998	1,614	3,409	28,285	130,420
31	1	900	1	2	0	-210	-1,212	9	894	1,052	94,510
32	1	900	1	2	10	-245	-2,161	201	1,177	6,048	104,490
33	1	900	1	2	20	-319	-1,487	716	2,142	17,621	126,895
34	1	900	1	2	30	-400	-1,389	1,426	3,499	26,105	167,520
35	1	900	1	2	40	-546	-1,670	2,054	4,663	26,690	201,770
36	1	900	1	2	50	-625	-1,507	3,069	6,143	26,925	185,530
37	1	900	1	2	0	-631	-2,327	13	1,012	1,595	109,270
38	1	900	1	2	10	-690	-2,337	546	1,938	23,604	160,790
39	1	900	1	2	20	-724	-2,270	1,568	3,252	53,250	201,730
40	1	900	1	2	30	-917	-4,471	2,524	8,670	68,985	544,100
41	1	900	1	2	40	-1,112	-4,855	4,191	8,787	76,530	448,630
42	1	900	1	2	50	-1,233	-2,730	5,515	12,583	77,675	512,900
43	1	900	1	2	0	-429	-1,817	19	721	2,346	67,715
44	1	900	1	2	10	-495	-2,389	422	1,690	16,895	165,945
45	1	900	1	2	20	-588	-1,797	1,276	2,543	37,718	164,700
46	1	900	1	2	30	-767	-1,980	2,372	4,309	51,260	275,285
47	1	900	1	2	40	-927	-1,961	3,607	6,981	54,720	212,765
48	1	900	1	2	50	-910	-3,288	4,255	8,730	67,155	356,885
49	1	900	1	2	0	-181	-851	11	539	1,959	48,562
50	1	900	1	2	10	-163	-885	116	724	7,962	68,660
51	1	900	1	2	20	-159	-588	290	932	11,046	64,310
52	1	900	1	2	30	-220	-1,127	602	1,787	18,318	85,940
53	1	900	1	2	40	-264	-823	887	2,253	19,543	105,735
54	1	900	1	2	50	-290	-812	1,269	3,086	20,432	85,565
55	1	900	1	2	0	-218	-1,360	-9	476	-1,126	50,925
56	1	900	1	2	10	-199	-1,151	153	780	6,953	85,165
57	1	900	1	2	20	-240	-1,552	442	1,197	16,814	93,440
58	1	900	1	2	30	-273	-746	792	1,589	23,744	88,380
59	1	900	1	2	40	-328	-1,178	1,154	2,789	25,960	118,650
60	1	900	1	2	50	-348	-843	1,541	3,138	27,882	111,370

It can be found from the results that the global ice loads are quite varying with different ice parameters. Among four parameters, the dominant factors are ice thickness and drift speed. In most cases, the ice loads are increased when the value of ice parameters are increased. Furthermore, the ice loads are increased when the heading of the vessel is increased in the sense of the mean value. However, the above results do not apply in maximum values. The maximum values are highly fluctuated and sometimes have lower values even in larger heading angle with higher ice parameters. This shows the uncertainty of the global ice loads in pack ice condition.

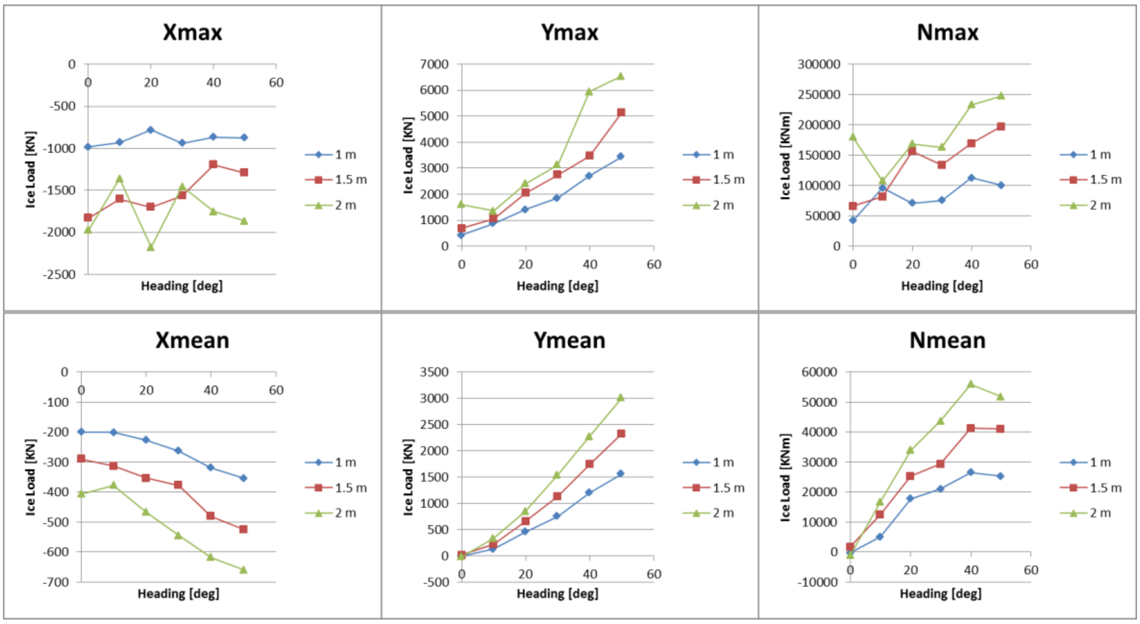

Figure 6. The estimated ice loads according to ice thicknesses

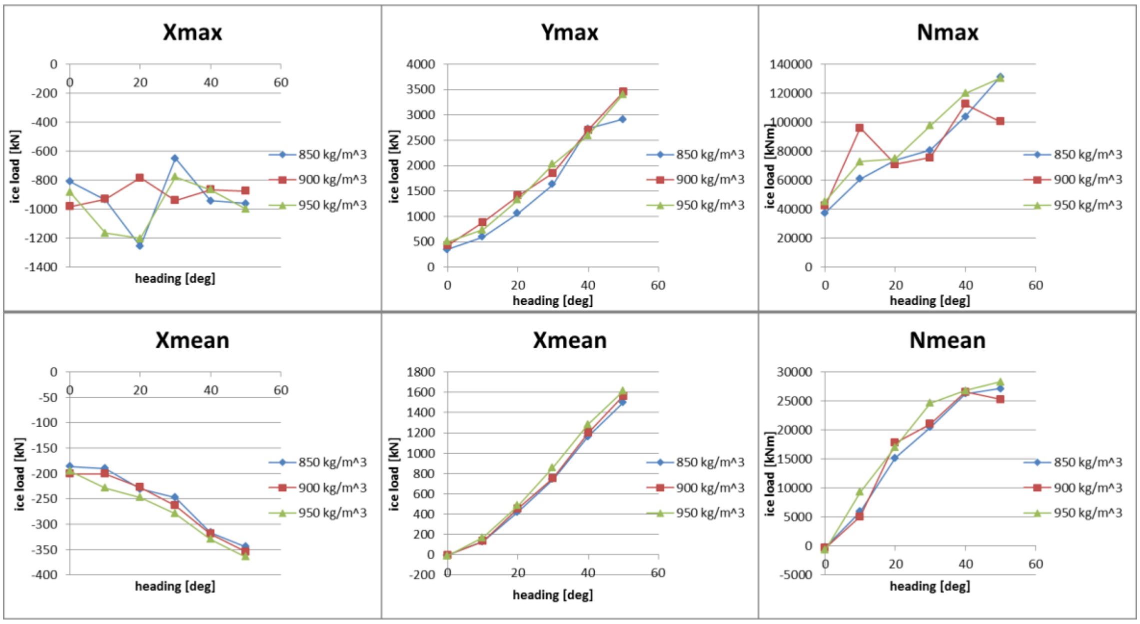

Figure 7. The estimated ice loads according to ice density

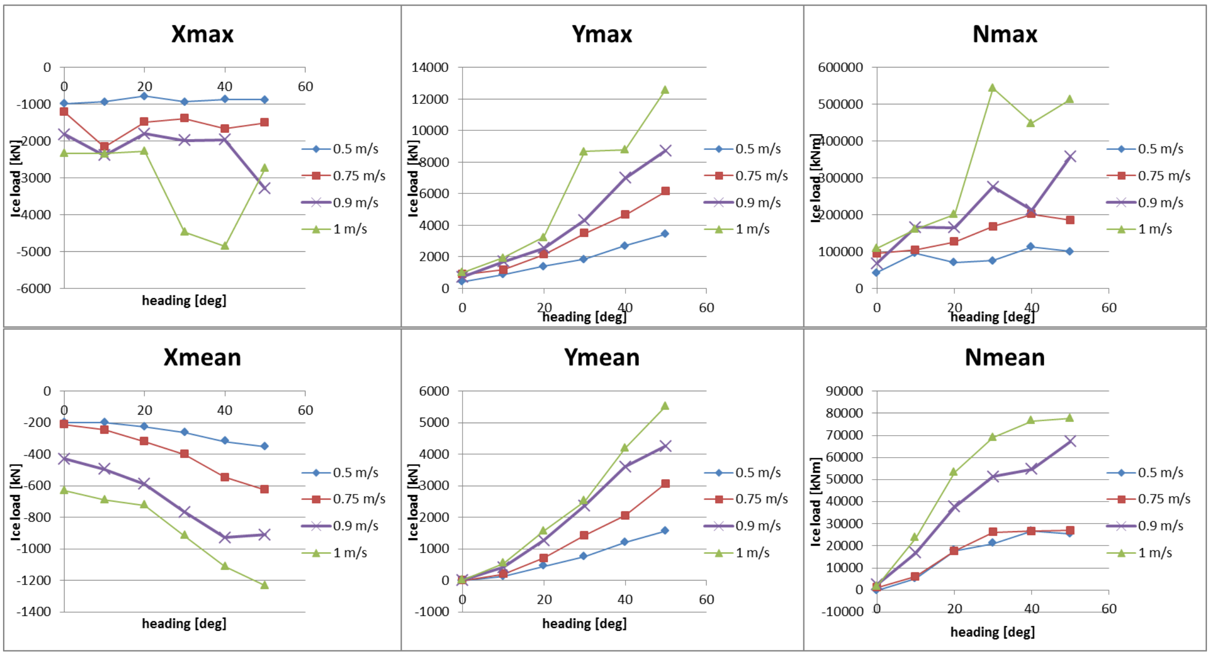

Figure 8. The estimated ice loads according to ice drift speed

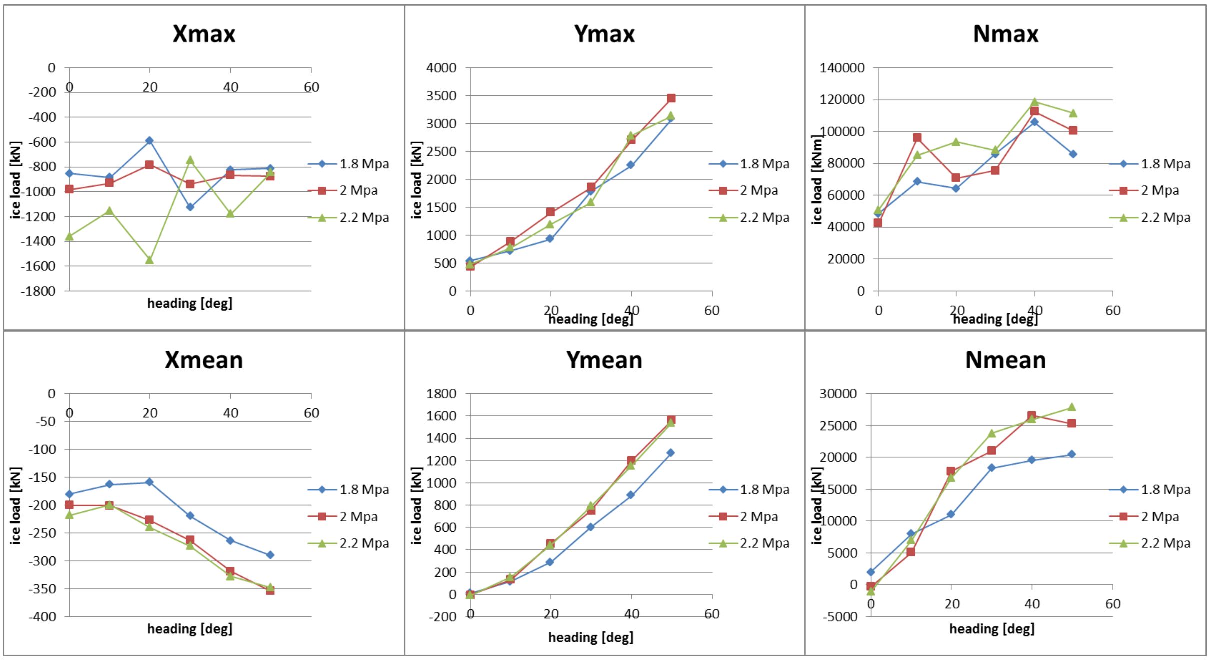

Figure 9. The estimated ice loads according to crushing parameter

DP CAPABILITY OF THE ARCTIC FPSO

The Arctic FPSO adopts a turret mooring system, which provides load-transfer mechanism between mooring system and the vessel. It also provides the mechanism for the ice-vaning capability. Therefore, the vessel can easily maintain the heading into the predominant environment. In this paper, it is assumed that the ice is coming from the same direction which is limited from -50 degree to 50 degree. The current, wind and wave loads are not considered in DP capability analysis.

It is assumed that the DP system of the Arctic FPSO has two bow tunnel thrusters of 3,000 kW capacity and three aft azimuth thrusters of 5,500 kW capacity. The thruster arrangement is summarized in Table 2. In total, the thrusters can give approximately 2.8 MN thrust including 10% of thrust degradation to cope with thruster-hull interaction. In order to investigate the DP capability, we followed the procedures proposed by IMCA with the significant values of the estimated global ice loads.

In the capability analysis, the ice loads are to be counterbalanced by the thrusters for maintaining the desired position. There are three components of ice loads F_x, F_y and M_z. Therefore, the thruster system must be able to provide three independent force components as follows:

$$\begin{aligned} -F_x &= \sum_{i=1}^{N} T_i \cos\alpha_i, \\ -F_y &= \sum_{i=1}^{N} T_i \sin\alpha_i, \\ -M_z &= \sum_{i=1}^{N} (-y_i T_i \cos\alpha_i + x_i T_i \cos\alpha_i), \end{aligned} \tag{9}$$

where T_i is thrust from *i* th thruster, α_i is the direction of the *i* th thruster, x_i and y_i are is position from a rotational center.

The equality in Eq. (9) can be achieved by minimizing the sum of relative utilization:

$$J = \sum_{i=1}^{N} \left(\frac{1}{W_i} \frac{T_i}{T_{max,i}} \right)^2 \tag{10}$$

where N is the number of thrusters and W_i is a weight.

Table 2. Thruster arrangement

No	Type	x [m] from mid-ship	y [m] from mid-ship	power [kW]	thrust [kN]
1	T/T	91	0	3000	330
2	T/T	86	0	3000	330
3	A/T	-113	-6.5	5500	875
4	A/T	-113	6.5	5500	875
5	A/T	-122	0	5500	875

When the required forces are found, these are allocated to each thruster using the thrust allocation algorithm. If the allocated thrust T_i exceeds its maximum value $T_{max,i}$, the relative utilization becomes greater than 1.0. This means that the DP system is not able to balance the external ice loads and thus DP fails.

In this paper, the DP capability analysis was conducted by using a thrust allocation algorithm that is developed as in-house code in SHI. Four capability plots in Figures 10 - 13 are made based on the DP capability analysis with the varying parameters of the ice thickness, ice density, ice drift speed, crushing strength of ice. It should be noted that regardless of which ice parameter that is varied, the other parameters remain fixed. Figures 10 - 13 show the effect of ice thickness, ice density, ice drift speed, and crushing strength of ice on DP capability, respectively.

It can be found from the results that the DP capability of the Arctic FPSO in pack ice is restricted by a narrow heading range up to 25 degree with current thruster capacity and configuration as in Table 2. The main reason for this is that the hull becomes more exposed to the ice collisions that are severely higher environmental loads when the heading of the vessel becomes large. It can be also found that among four ice parameters that are varied the DP capability is highly dependent on the ice drift speed and ice thickness. Small changes in those two parameters result in large changes in DP performances as in Figures 10 and 12.

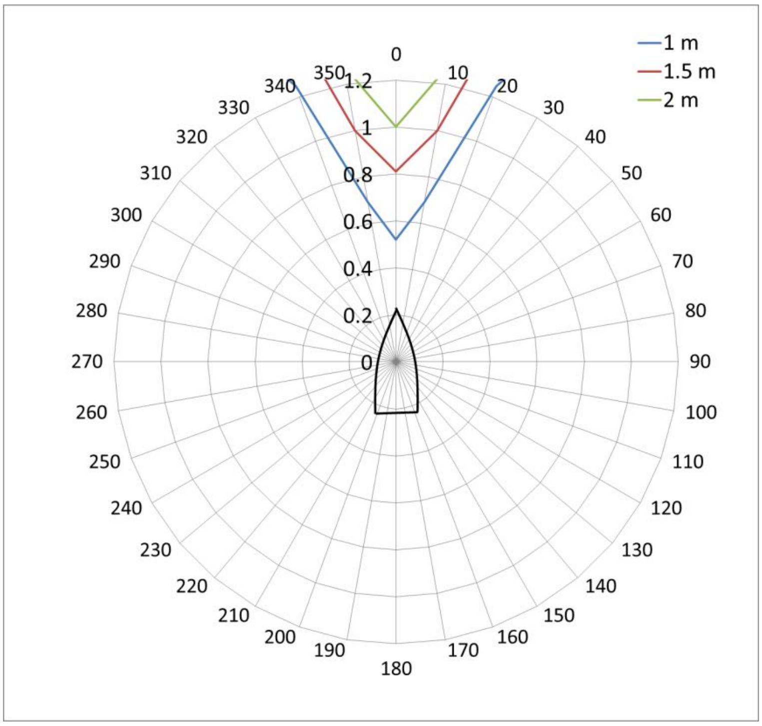

Figure 10. DP capability plot according to varying ice thickness

(Density 900 kg/m^3, Drift speed 0.5 m/s, Crushing strength 2Mpa)

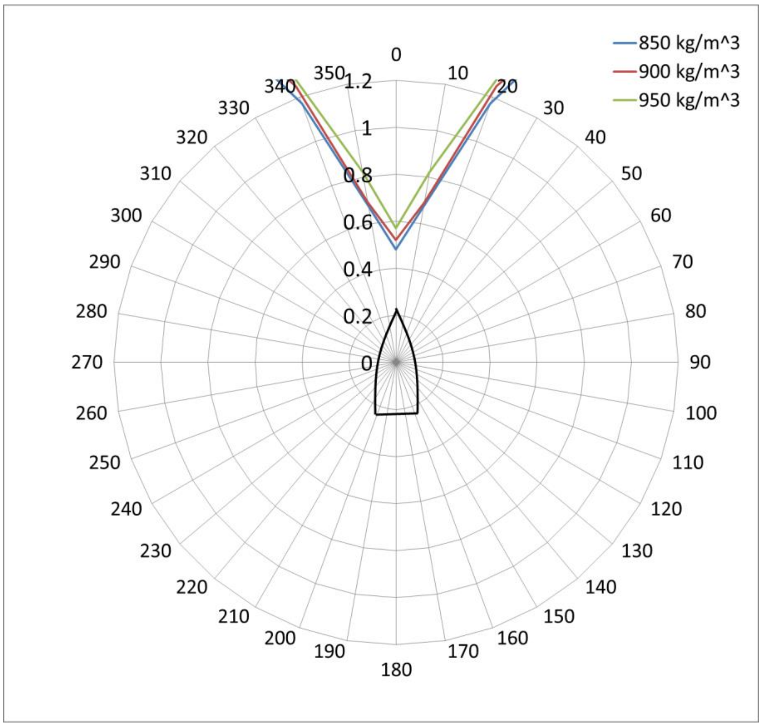

Figure 11. DP capability plot according to varying ice density

(Ice thickness 1 m, Drift speed 0.5 m/s, Crushing strength 2Mpa)

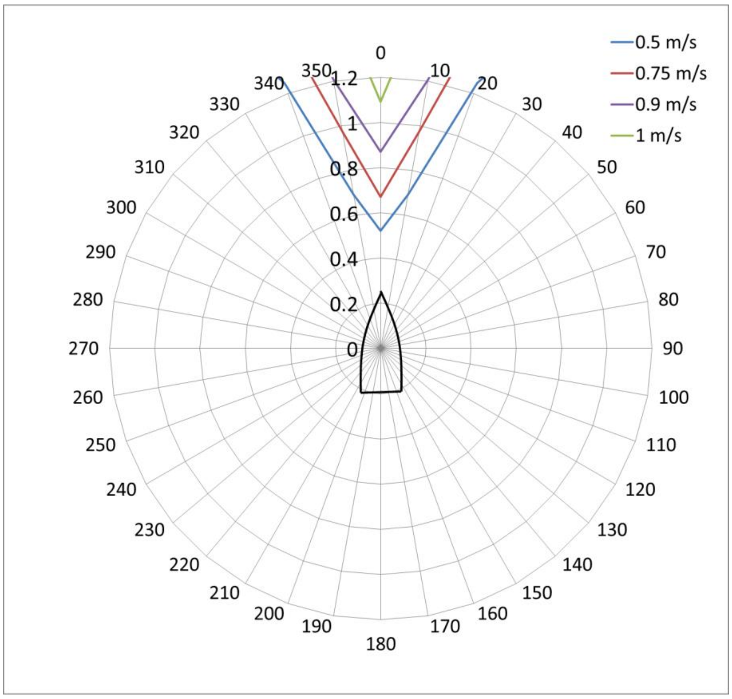

Figure 12. DP capability plot according to varying ice drift speed

(Ice thickness 1 m, Density 900 kg/m^3, Crushing strength 2Mpa)

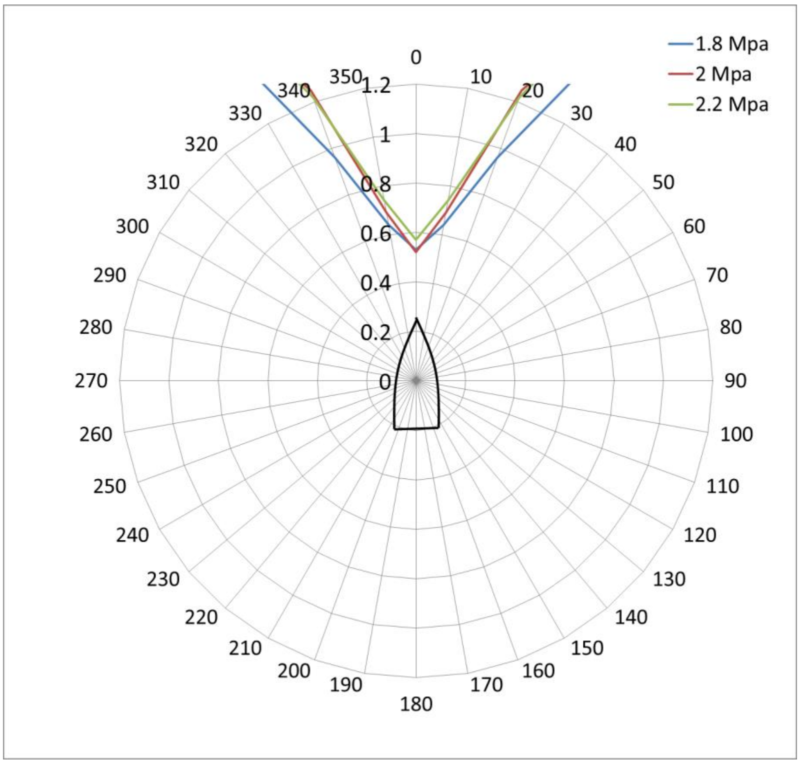

Figure 13. DP capability plot according to crushing strength of ice

(Ice thickness 1 m, Density 900 kg/m^3, Drift speed 0.5 m/s)

CONCLUSIONS

In this paper, the ice load simulator GEM that is developed by Memorial University has been used to investigate the global ice loads on the Arctic FPSO that is conceptually designed by Samsung Heavy Industries. The effects of various ice parameters on the global ice loads have been also examined through a series of ice-towing simulations.

To evaluate the DP performance of the Arctic FPSO in pack ice condition, a static DP-ice capability analysis was conducted by using the estimated ice loads and the in-house thrust allocation algorithm. The results were presented in a DP-ice capability plots according to IMCA that is widely used as a common format. In this paper, four radial parameterizations of the polar plot are presents for ice thickness, density, drift speed, ice strength. Although the results are not validated with model tests or field data, these results can be used qualitatively for the design of the capacity and configuration of thrusters and mooring system.

The precision and validity of the ice load simulator still remain to be solved and verified. It is noted that the results in this paper related to the global ice loads and DP capability should be treated indicatively and illustratively as several numerical challenges. However, it is worthwhile to note that the systematic procedure utilized to create the capability plots, where a numerical simulator is employed to estimate the global ice load, can give insights for analysis of the performance of an Arctic vessel in pack ice conditions.

In addition, uncertainties related with thruster-ice interaction, how to deal with dynamic ice loads shall be investigated in detail with the ice model tests or real-ship measured data with inherent dynamic effects (margin).

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