Ice Belt Extents for Protection in Waves

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INTRODUCTION

Floating ice is a significant hazard to ships operating in polar regions. In addition to ice fields that can be observed and monitored from satellites, ships must also contend with ice drifting away from ice fields, as well as ice calved from glaciers and ice shelves. This can lead to a proliferation of icebergs, bergy bits and growlers in waters that are otherwise 'ice free'. Bergy bits[1] and growlers[2] are of particular concern. Due to their smaller size they are more difficult to detect visually or using radar, especially amongst waves, in darkness or poor visibility, yet they have the potential to breach watertight integrity. Ice in polar waters is often multi-year sea ice, or ice of land origin, both of which are stronger and more damaging than first year sea ice.

Incidents highlighting the risk posed by floating ice in polar waters include:

- BCM Atlantic (2000): Trawler built to DNV Ice Class A, sank after striking ice at 6-7 knots;
- MV Explorer (2007): Adventure tourism passenger vessel built to DNV Ice Class A, sank after striking ice of land origin at a speed of 4-5 knots
- Snow Dragon (2019): Chinese research icebreaker, struck an iceberg that was not detected due to poor visibility at around 3 knots. Damage was sustained to the ships mast and bulwarks.

To mitigate the risk posed by floating ice, polar vessels incorporate structural ice protection, in the form of thicker plating and stronger frames around the waterline. Internationally agreed minimum requirements for polar vessel design are embodied in the IMO Polar Code (IMO, 2014), which references IACS Polar Class Rules (IACS, 2016) for structural ice protection requirements.

The risk of ice damage may be increased by waves causing the instantaneous waterline to be above or below the extents of structural ice protection, whether transiting an apparently 'ice free' area, or an observed ice field. Data from one wave buoy deployed in the Ross Sea as part of a programme to characterise the Southern Ocean and Ross Sea wave environment (Garrett & Durrant, 2019) indicated a mean significant wave height of 3.4m (Sea State 5) from the time of deployment in 3/10th ice coverage, until it became fast in 10/10th ice. The greatest significant wave height over this period was 10.8m (Figure 1). Waves in this marginal ice zone are driven by the ocean swells circumnavigating Antarctica, with no shielding land mass.

[1] Typically 100 – 300m^2 in area, protruding 1-5m above the water.
[2] Typically 20m^2 in area, and protruding less than 1m above the water.

Therefore, it must be assumed that vessels operating in Antarctic marginal ice zones will encounter waves together with floating ice.

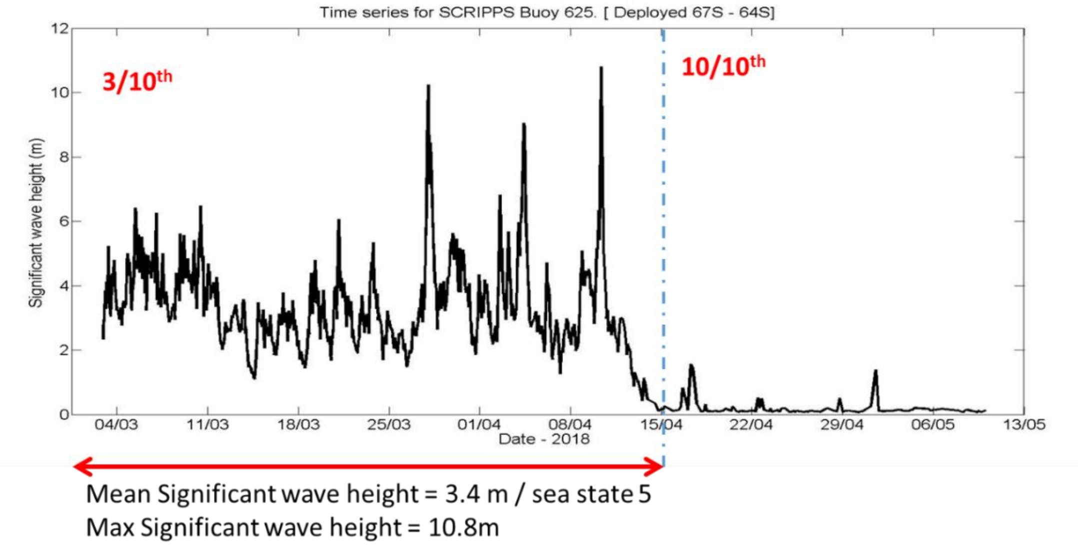

Figure 1: Significant Wave Height Data from Wave Buoy Deployed in Ross Sea Marginal Ice Zone, March / April 2018

The Royal New Zealand Navy (RNZN) conducts summer patrols to the Ross Sea, to support the Ministry of Primary Industries with its fisheries monitoring and compliance activities under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR). From the early 2020s, the RNZN will transport fuel and supplies to McMurdo Sound using the new Polar Class tanker HMNZS AOTEAROA, and a dedicated Southern Ocean Patrol Vessel is also planned to enter service from 2027 onwards. Noting the current and future level of polar operations, together with the ice hazard described, the RNZN commissioned seakeeping analysis on a number of representative hullforms, to understand the level of protection that IACS Polar Class ice belt extents provide to vessels operating in waves. This paper presents some of the findings and conclusions from this analysis, building on earlier work by the NZ Defence Technology Agency (DTA) and MARICO Marine NZ Ltd (DTA, 2018).

STRUCTURAL ICE PROTECTION – POLAR CLASS RULES

IACS Polar Class Rules (the Rules) are appropriate for ships operating in areas where multi-year ice may be expected. For ships other than icebreakers, the Rules allow for varying levels of ice protection: from PC1 to PC7, where PC1 is the most ice capable. The design case for all Polar Classes is a glancing ice impact at the bow; this impact load is scaled to account for the expected loads on different areas of the hull. Unless the ship is stern acting, the highest loads are expected at the bow, and in the 'ice belt' region around the waterline. For example, in the midbody region of a PC5 vessel, in the ice belt the ice load is 50% of the bow impact load, below the ice belt the load is 30% and on the bottom the load is 0%. Ice belt extents are defined by the location of the Upper and Lower Ice Waterlines (UIWL, LIWL), as shown in Figure 2. This is a simplified version of the hull areas defined in the Rules, which divide the hull further into different longitudinal regions. For the purpose of this investigation, Polar Class 'ice belt extents' were taken as including both the bow region and the ice belt aft of the bow region, together representing the areas of greatest ice reinforcement.

The design load corresponds to the single highest load that is expected to occur once per year by a ship operating in ice infested waters, in ice conditions commensurate with the PC rating of the vessel (IACS, n.d.). The effect of ship speed is combined with ice strength and thickness in a single 'Class Factor', and therefore the design ice load could equally be achieved at low speeds / stronger ice, or higher speed (e.g. transit speeds) / weaker ice. The Rules allow for a degree of permanent set in the plating and framing, under the design load.

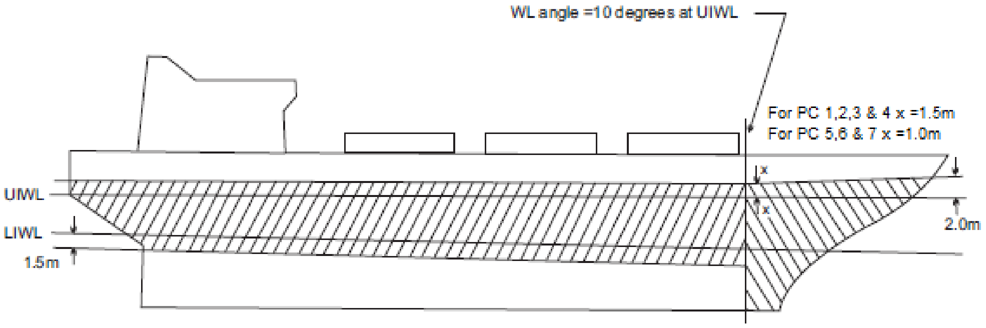

Figure 2: Polar Class Ice Belt Extents (Simplified)

ICE BELT EXTENTS ANALYSIS

Vessel Characteristics

Four vessels have been investigated, a conventional Offshore Patrol Vessel (OPV), two versions of a Polar Patrol Vessel (PPV) and a naval tanker design. The characteristics of the vessels are summarised in Table 1.

Table 1 Vessel Dimensions and Loading Conditions

Characteristic	Units	Offshore Patrol Vessel	Polar Patrol Vessel		Naval Tanker	
			PPV-A	PPV-B	Polar Light	Polar Deep
Description	-	Conventional hullform, bilge keels, fin stabilisers, twin screw, twin rudder	Ice bow, fin stabilisers, twin skeg, twin screw, twin rudder	As for PPB-A, but with 8m midship stretch	Twin skeg, twin screw, twin rudder, bilge keels	
Polar Class	-	No	Yes	Yes	Yes	Yes
Length Between Perpendiculars	m	73.5	86.4	94.4	168.7	
Beam	m	14.0	19.0		24.5	
Mean Draught	m	3.8	5.7		7.0	8.4
Displacement	t	1900	5700	6500	21000	26100
Block Coefficient, C_B	-	0.49	0.61	0.64	0.73	0.75
Prismatic Coefficient, C_P	-	0.67	0.69	0.72	0.75	0.77

Analyses were performed for a range of vessel headings from head seas to stern seas at 15-degree intervals. The vessel speeds ranged between zero and a maximum of either 16 knots (OPV) or 15 knots (PPVs and Naval Tanker).

Analytical Methods

Hydrodynamic analyses for the vessels were performed using the 3D diffraction analysis software HydroStar, developed by Bureau Veritas, to determine the motions and relative motions characteristics of the vessels.

A mesh for each vessel at the selected loading condition draught was used to compute the vessel motions and relative motions Response Amplitude Operators (RAOs). The motions of the vessel incorporate non-linear damping effects via the use of linear and quadratic damping components. As part of the 3D potential flow analysis, HydroStar calculates the velocity potential throughout the fluid domain surrounding the vessel, accounting for the radiated and diffracted wave fields. The velocity potential at the surface around the vessel allows the fluid pressure to be determined, from which amplitude and phasing of the wave elevation above the mean water level can be calculated at selected locations (e.g. Figure 3). Combining the absolute vertical motions at points on the vessel with the adjacent wave surface elevation allows the motions (amplitude and phasing) of the water surface relative to the hull to be determined.

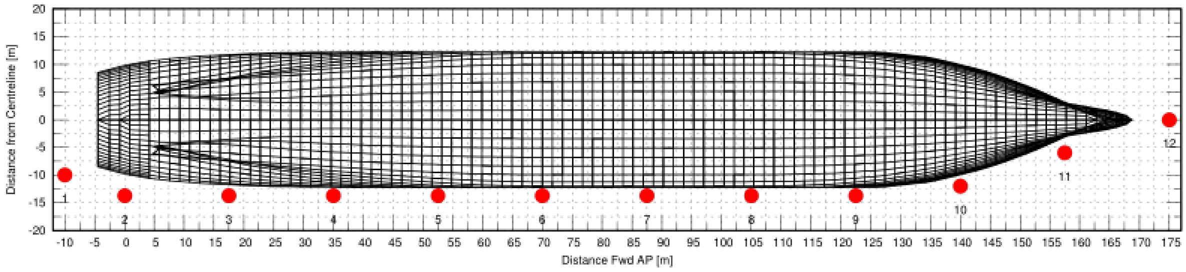

Figure 3: Example of Locations of Relative Wave Elevation Calculations, Plotted Against Hull Mesh to Waterline

Statistical Methods – Ice Belt Effectiveness

Assuming that the wave spectral density $S_w(\omega)$ represents the distribution of the wave energy and that RAO(ω) represents the transfer function of any first order quantity (motions, accelerations, relative wave elevation etc.), the spectral density of the first order responses can be defined as:

$$S_R(\omega) = RAO^2(\omega) \times S_w(\omega) \qquad [1]$$

The spectral moments of the responses can then be defined as:

$$m_n = \int_0^\infty \omega^n S_R(\omega) d\omega \qquad [2]$$

From the spectral moments, statistical properties of the responses such as the variance, m_0, are able to be calculated.

Assuming that the response is a narrow-banded Gaussian process, the distribution of instantaneous response amplitudes is given by the Normal distribution. Assuming zero mean response, the cumulative distribution of the instantaneous response *x* is given by:

$$P(x) = \frac{1}{2}\left[1 + erf\left(\frac{x}{\sqrt{2m_0}}\right)\right] \qquad [3]$$

The distribution of instantaneous response amplitudes can be used to determine the proportion of time for which the sea surface remains within the vertical extents of the ice belt. If the upper and lower extents of the ice belt relative to the mean waterline of the vessel at a particular loading condition are given by $Z_{IB,Upper}$ and $Z_{IB,Lower}$ respectively, the probability of the water surface lying between those values is given by:

$$P(Z_{IB,Lower} < x < Z_{IB,Upper}) = \frac{1}{2}\left[1 + erf\left(\frac{Z_{IB,Upper}}{\sqrt{2m_0}}\right)\right] - \frac{1}{2}\left[1 + erf\left(\frac{Z_{IB,Lower}}{\sqrt{2m_0}}\right)\right] \quad [4]$$

Figure 4 illustrates this method, showing how the relative wave elevations are normally distributed about the mean waterline. Depending on the heights relative to the waterline of the upper and lower limits of the ice belt at a particular longitudinal position, the probability of the sea surface being within the ice belt is found from the area under the normal distribution between these upper and lower bounds (shown shaded red).

This probability (Equation [4]) was used as an appropriate metric of ice belt effectiveness. The implicit assumption is that ice impacts will occur at the instantaneous waterline; this is imperfect, however it is thought to be generally representative of the coverage provided by the ice belt.

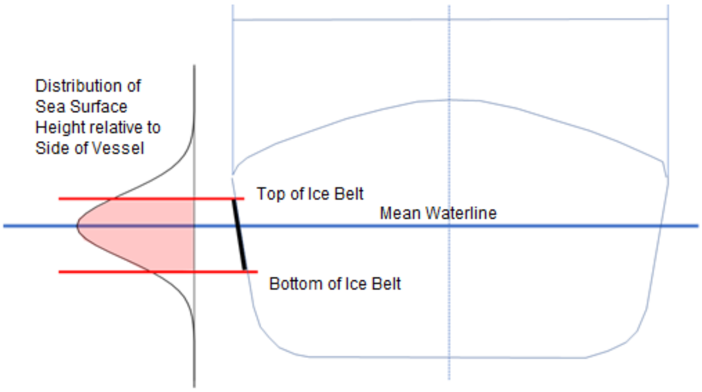

Figure 4: Normally Distributed Relative Wave Elevations

Wave Environment in Southern Ocean and Ross Sea

Wave spectra were developed from wave measurements recorded by wave buoys deployed in the Southern Ocean and Ross Sea (Garrett & Durrant, 2019), using a clustering technique designed to provide a limited number of spectra that were most representative of the entire recorded population.

Wave height was calculated for each wave measurement sample using spectral moments, allowing grouping based on the band in the Douglas Sea Scale they fell into, with sea states 3, 5 and 7 being of interest[3]. The waves in each sea state band were then used as input to a clustering of curves analysis using the CLARA algorithm, set up using the methods described by Hamilton (2010). Ten output medoids (the spectral curves which best describes each cluster of data) for each sea state grouping and location were used as representative spectra. Figure 5 and Figure 6 present the 10 medoid spectra for the Ross Sea and Southern Ocean wave conditions respectively.

[3] No sea state 3 conditions were recorded in the Southern Ocean.

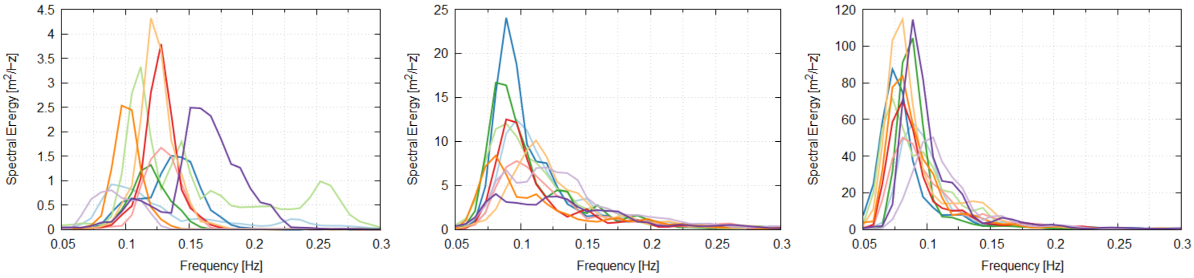

Figure 5: Ross Sea Medoid Spectra, Sea States 3 (left), 5 (centre) and 7 (right)

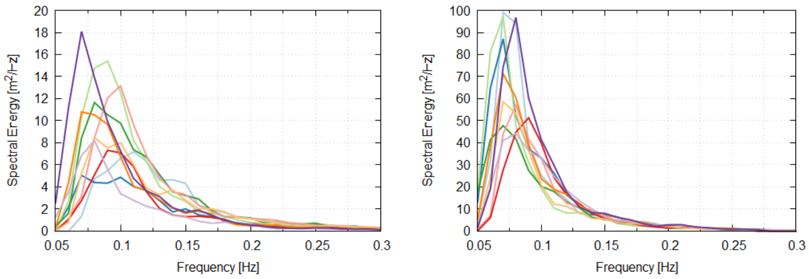

Figure 6: Southern Ocean Medoid Spectra, Sea States 5 (left) and 7 (right)

Analytical ITTC Wave Spectra

To provide a basis for comparison, analyses were also performed using the ITTC two parameter spectrum, which is defined in terms of significant wave height H_{sig} and peak period T_p as follows. This spectrum is commonly used to define open ocean conditions:

$$S_{ITTC}(\omega) = \frac{5}{16} H_s^2 \omega_p^2 \omega^{-5} exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-1}\right) \qquad [5]$$

Wave Spreading

Wave spreading was accounted for by using a *cos n* type function, whereby the directional short-crested wave spectra S(ω,θ) can be expressed in terms of the unidirectional wave spectra as follows:

$$S(\omega,\theta) = S(\omega)D(\omega,\theta) = S(\omega)D(\theta), \qquad [6]$$

where,

$$D(\theta) = \frac{\Gamma\left(1+\frac{n}{2}\right)}{\sqrt{\pi}\Gamma\left(\frac{1}{2}+\frac{n}{2}\right)} cos^n(\theta - \theta_p). \qquad [7]$$

The primary wave direction is given by θ_p and typical values for n for wind seas are between 2 and 4. For the present analyses a value of 2 was used.

RESULTS

Ice Belt Effectiveness in Ross Sea and Southern Ocean Spectra

Polar plots were developed indicating ice belt effectiveness in Southern Ocean and Ross Sea conditions. The results represent P_{min}, the lowest probability (worst-performance) across all of the points calculated along the length of each vessel.

Figure 7 illustrates the relative performance of the PPV-A, PPV-B and Naval Tanker (Polar Light and Deep) vessels with ice belt extents corresponding to PC1-4 and PC5-7 requirements[4]. The sea conditions represented are the weighted average of the 10 Ross Sea, Sea State 7 spectra. For each vessel, it is clear that the larger PC1-4 ice belt extents result in an increased probability of the sea surface lying within the ice belt.

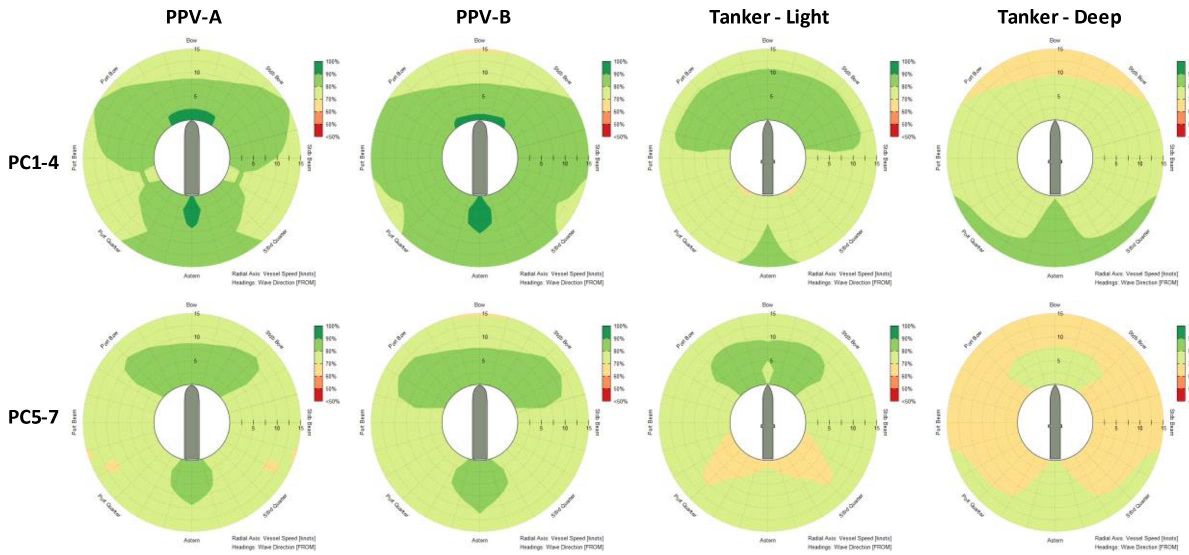

Figure 7: Comparison of Effectiveness of Different Ice Belt Extents, Ross Sea, Sea State 7

For Sea States 3 and 5, the ice belt effectiveness P_{min} was high, with vessels generally having greater than 90% ice belt effectiveness at speeds of 0 to 15 knots[5].

Ice Belt Effectiveness Results in ITTC Spectra

The spectra found via the clustering process exhibit characteristics which in many cases are quite dissimilar from common analytical spectra. Consider as an example Spectrum 1 for the Ross Sea, Sea State 7 conditions. Figure 8 compares this spectrum against an ITTC analytical spectrum, which has the same nominal H_{Sig} and T_p. It can be seen that the ITTC spectrum has a broader energy spread than the cluster spectrum, with a much lower peak.

[4] Note that Polar Class ice belt extents are grouped into PC1-4, and PC5-7. See Figure 2.

[5] The exception was the naval tanker in Polar Deep condition, with PC5-7 extents, for which P_{min} was found to be 80-90% throughout the same speed range.

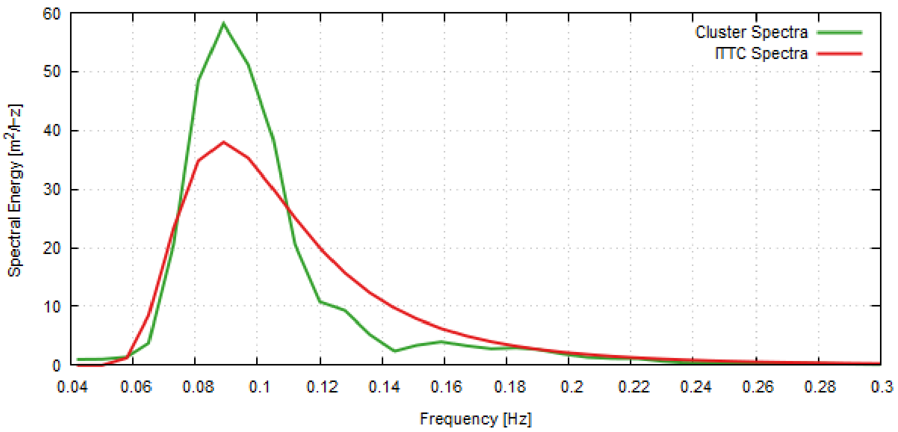

Figure 8: Comparison of Ross Sea, Sea State 7, Spectrum 1 with corresponding ITTC Spectra

Figure 9 compares the ice belt effectiveness of the ice belts on each vessel in the selected wave conditions for cluster and ITTC spectra. It can be seen in this particular case that the cluster spectra typically result in better ice belt effectiveness, with a wider range of conditions having green or dark green colouring.

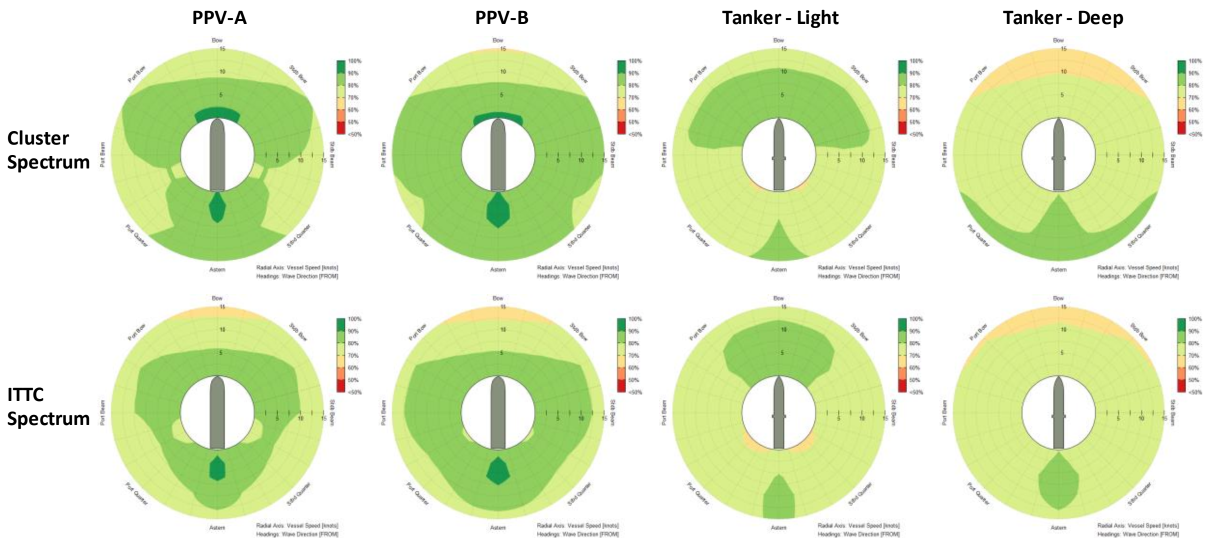

Figure 9: Comparison of Effectiveness of Different Ice Belt Extents, Ross Sea, Sea State 7 versus equivalent ITTC Spectra

The improved ice belt performance in the cluster spectra can be explained by the relationship between the distributions of wave energy in the spectra and the relative wave elevation (RWE) responses. Consider the relative wave elevation RAOs at the bow of the vessels in bow quartering seas at a speed of 10 knots. Figure 10 compares the cluster and ITTC spectra against the relative wave elevations for each of the vessels. It can be seen that the peak RWE responses for the tanker are much closer to the peak period of the waves and so are more affected by the concentration of wave energy in that region of the cluster spectra. The PPV vessels have their peak RWE response at a higher frequency, away from the majority of the wave energy for both spectra.

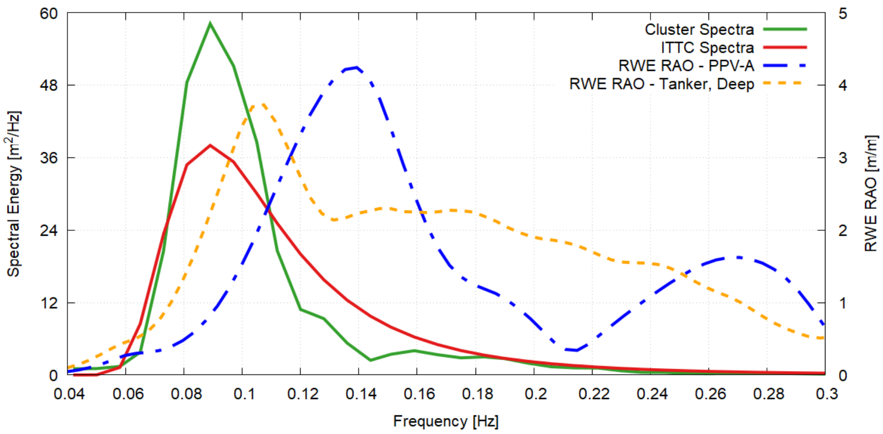

Figure 10: Comparison of Cluster and ITTC Spectra Against Relative Wave Elevation RAOs

This example illustrates the importance of correctly specifying the form of the wave spectra, as even for the same nominal H_{Sig} and T_p, the vessel performance may differ significantly. Whether that difference results in an under- or over-prediction of vessel performance will depend on the frequency dependent characteristics of the particular vessel response.

Ice Belt Effectiveness – General Performance Curves

Whilst the ice belt effectiveness results for the representative Polar Class vessels in general demonstrate a high degree of coverage, the results are significantly influenced by the location of the UIWL and LIWL (Figure 2). For example, the tanker has a large difference between the two waterlines due to its operating both at full cargo deadweight and empty in polar waters, which results in generous ice belt extents.

In order to understand required ice belt extents in a more general sense, performance curves were generated from the response variance results m_0, using Equation [4]. The specific m_0 results used were the weighted average results across the Southern Ocean spectra, at all headings.

Two examples corresponding to Sea State 5, Southern Ocean at 10 knots are presented in Figure 11. The variation of P (Equation [4]) is plotted with respect to H / T_{mean}, where H is the total ice belt height outside of the bow region, and T_{mean} is the mean draught for the considered loading condition. With reference to Figure 2:

$$H = 1.5\text{m} + (UIWL - LIWL) + \begin{cases} 1.0\text{m (PC5-7)} \\ 1.5\text{m (PC1-4)} \end{cases} \quad [8]$$

To produce these curves, the arrangement of ice protection was assumed to be as per Polar Class[6] (Figure 2), but UIWL was nominally raised or lowered to generate results for a wider range of H, whilst keeping T_{mean} fixed. The minimum possible H is 2.5m, when UIWL = LIWL

[6] It should be noted that results for OPV are somewhat artificial, because the basis vessel could not sustain the weight of Polar Class ice protection. However, the inclusion of this vessel helps to demonstrate the effect of different hullforms on ice belt performance.

and PC5-7 extents are applied, although this is clearly only a theoretical case. Parallel sinkage due to additional structural weight was neglected.

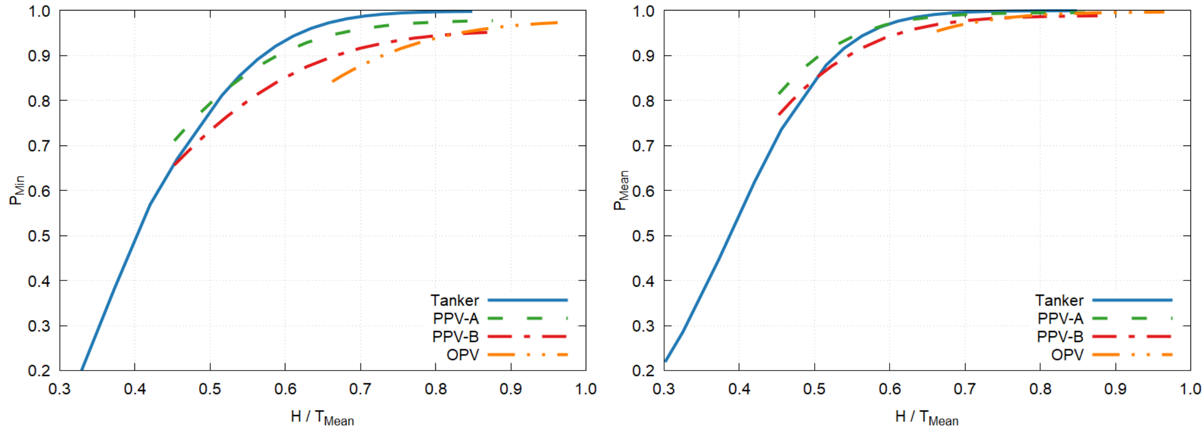

Figure 11: Ice Belt Effectiveness (Minimum (left) and Mean (right) Across All Waterline Locations). Sea State 5, 10 knots, Southern Ocean.

Determining ice belt effectiveness P by considering only the worst-case location along the waterline (P_{min}) is conservative, implicitly assuming that ice impact will occur at the worst-case location. A more realistic assumption would be that impact is equally likely to occur anywhere along the waterline (as represented by P_{mean}, the average performance of all locations along the waterline). When P_{mean} is taken as the measure of ice belt effectiveness, the results collapse down approximately onto a common performance curve. This suggests that, for this sea state and speed, ice belt effectiveness is determined largely by H / T_{mean}, and is not otherwise sensitive to hullform characteristics or principal particulars.

Performance curves for a range of sea states and ship speeds confirmed this insensitivity amongst the basis vessels, with the slight exception being sea state 5 / 3 knots (Figure 12), in which ice belt effectiveness of the OPV hullform is stepped below that of the other vessels. This is caused by significant roll at low speeds due to a hullform with low natural roll damping.

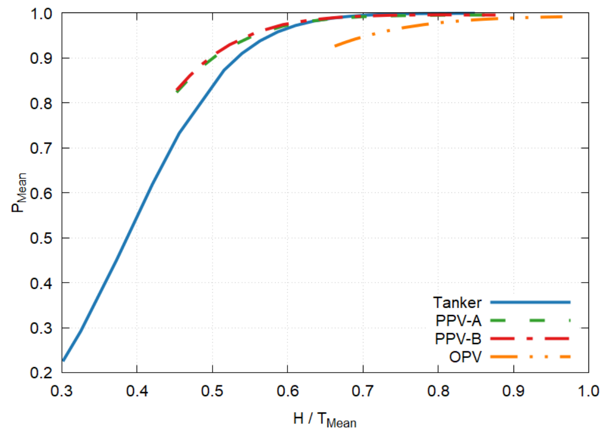

Figure 12: Ice Belt Effectiveness (Mean Across All Waterline Locations). Sea State 5, 3 knots, Southern Ocean.

P_{mean} results for all four hullforms combined[7] are presented in Figure 13. It was found that, for any given value of H, results for 'PC5-7' extents were nearly identical to those for 'PC1-4' extents. This is because, in fixing H the only difference between the two was the absolute height (above baseline) of the upper ice belt extent at the stem.

Unsurprisingly, ice belt effectiveness is reduced in higher sea states, and at higher speeds. Increasing H / T_{mean} leads to an increase in ice belt effectiveness, however beyond H / T_{mean} = 0.6, diminishing returns apply.

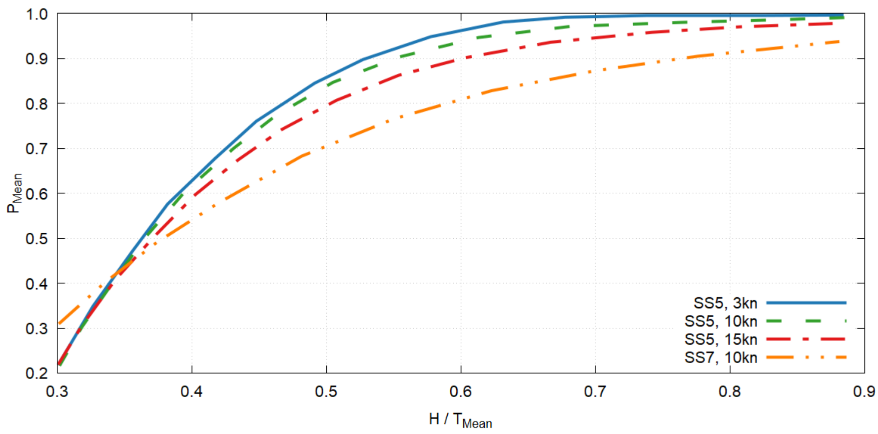

Figure 13: Ice Belt Effectiveness, in Southern Ocean Wave Conditions.

POLAR VESSEL DESIGN IMPLICATIONS

It would be difficult to set an 'acceptable' value of ice belt effectiveness, as this is only one component in determining the overall risk of structural damage due to collision with floating ice. Other factors include the prevalence of ice, the size, thickness and physical properties of ice and weather conditions, all of which are uncertain. However, high values of effectiveness must reduce the overall risk. For the basis Polar Class vessels H / T_{mean}, the ratio between total ice belt height and mean draught, is approximately 0.5 – 0.6 in the deepest loading condition. This provides typical ice belt effectiveness (Figure 13) of at least 85% at SS5 / 10 kn and 70% or greater even at SS7 / 10 kn.

While acknowledging the limited number of vessels contributing to this study, the results indicate that there may be little value in augmenting ice belt extents beyond Polar Class, to improve protection in waves, provided that:

- H / T_{mean} is greater than 0.5; and
- The vessel has good seakeeping performance, and in particular does not suffer from excessive roll and pitch in the operating wave conditions. This may be particularly problematic at low speeds, where fin stabilisers, if fitted, will be ineffective. Polar vessels need to operate at low speeds around ice and in waves, therefore seakeeping performance requirements should capture this. Analysis has shown that it is important

[7] Produced using the lower bound results. The SS5 / 3 knot curve excludes OPV results due to this vessel's roll low speed roll issue. The curve as plotted therefore represents vessels in which exhibit good seakeeping performance at low speeds.

to use the specific wave conditions for the area of operation, since ship motions are sensitive to the spectral energy distribution.

Statistical analysis of relative wave elevation data, as described in this paper, could be undertaken during initial design to further improve confidence in the protection that Polar Class ice belt extents provide in waves, for the specific hullform and operating parameters including wave environment, ship speeds and draughts.

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