DESIGN OF ICE BREAKING SHIPS

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Contents

Summary

The design of ice capable ships includes reaching an adequate performance, adequate hull and machinery strength and proper functioning of the ship in ice and in cold weather. Good ice performance requires hull shape that has a low ice resistance as well as allows different manoeuvres required. Good ice performance includes also a good propulsion thrust which can be achieved with propeller design and also designing the hull lines so that propeller-ice interaction is minimized. The adequate strength is achieved commonly by selecting a proper ice class and following the class rules. The designer must have some insight about ice loads in order to select the structural arrangement. This chapter describes the requirements for materials, equipment and general arrangement.

1. Designing an Ice Capable Ship

Understanding how ice is acting on a ship forms the basis of design of ships for ice. In this chapter some aspects of ship design for ice are covered, and mostly in a qualitative way. The reason for the qualitative approach is that no single and exact method for any aspect of ship design for ice exists. The designer is mostly forced to search for literature and then applies in various depths a multitude of methods found – and the final design is then a synthesis of results from different sources that the designer deems most appropriate. This judgment is at best if it is based on earlier experience; this makes ice design a difficult area as most valid experience is feedback from designs that have been realized and are operating in ice. The following outline about design aspects of ice capable ships should be considered as a general overview about design; the more exact numbers must be supplied by the detailed methods selected.

The design starting point is usually a functional specification (an example given in the box below) outlining the ice performance required. This specification is made often with interaction between the owner and a designer so that the different requirements are in balance. The balance of the different requirements ensures that no single requirement drives the design. Below is shown an extract of a detailed functional specification. Often the designer is given a free hand how the requirements are met but sometimes the owner has a clear idea of how the ship shall look like.

BALTIC ENVIRONMENTAL MULTIPURPOSE ICEBREAKER

The General Ice Performance Requirements

- **Average escort speed:** The average speed in all normal ice conditions in the operational area must be at least 8 - 12 knots;
- **Level ice ahead:** The ship speed must be at least 13 knots in 50 cm thick level ice with a flexural strength of 500 kPa and thin snow cover. The ship must be able to proceed with a 3 knots speed in 1.5 m thick level ice;
- **Level ice astern:** The ship must be able to go astern with 7 knots speed in 70 cm thick level ice (flexural strength 500 kPa, thin snow cover);
- **Maneuvering capability:** The ship must be able to turn on spot (180^o) in 70 cm thick level ice (flexural strength 500 kPa, thin snow cover) in max. 2.5 minutes. The ship must be able to turn out immediately from an old channel with 5 m thick side ridges;
- **Old channels:** The ship must be able to maintain a high speed in old channels. Especially in a channel corresponding to the requirement of IA Super ships, she has to maintain at least 14 knots speed;
- **Ridge penetration:** The ship has to be able to penetrate with one ram (initial speed 13 knots) a ridge of 16 m thickness;
- **Channel widening:** The ship has to be able to make a 40 m wide channel in 50 cm thick ice (500 kPa, thin snow cover) at speed 4 knots;
- **Performance in compressive ice:** The ship must be able to maintain a 9 knots speed in compressive ice of thickness 50 cm.

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- **Temperatures:** Air temperature -35^o— $+30^o$ and sea water temperature -1^o— $+32^o$.

2. Historical Development of Ice Capable Ships

A short historical note on the development of icebreakers and ice going ships is presented by noting the major steps in the evolution. The first ice breaking ships appeared in mid 1840's in Hudson River in the US and in the Elbe River in Germany. First dedicated icebreakers appeared in 1860's and 1870's in the St. Petersburg and Hamburg harbors. Before the turn of the century several dedicated sea-going icebreakers were in service. The development of merchant ships for ice started towards the end of 19^{th} century. The year-round navigation in the Baltic started in 1877 with the introduction of the ship Express II sailing between the ports of Turku and Stockholm.

The hull design of this ship and many similar ones followed that of the icebreakers; only the machinery power was larger in icebreakers.

Ships that were intended to sail independently in ice evolved in 1950's in the Soviet Union with the emergence of the Lena- and Amguema-series of ships (the latter is also called Kapitan Gotskij series). These ships had an icebreaking bow shape and a high strength for Arctic trade. Several series of Arctic ships has been built to Soviet and Russian owners (e.g. Norilsk and Norilsk Nikel-series) and to Finnish owners (Lunni-series) – the Canadian ships MV Arctic and MV Umiak 1 should be mentioned also. Since the early times the icebreakers and ice breaking ships have developed much based on several technological innovations, some of which are mentioned below.

The hull shape of the early icebreakers in the 19th century was characterized by a very small buttock line angle φ at the stem; values were usually smaller than 20^0 (definition of hull angles, see Figure 1). The buttock lines and waterlines were rounded and the sides were inclined ($\beta > 0$). The rounded stem developed quite late (in the 1980's) as a sharp bow was long deemed favorable for ice breaking. The principle of hull lines design is and has been to make the flare angle ψ as small as possible.

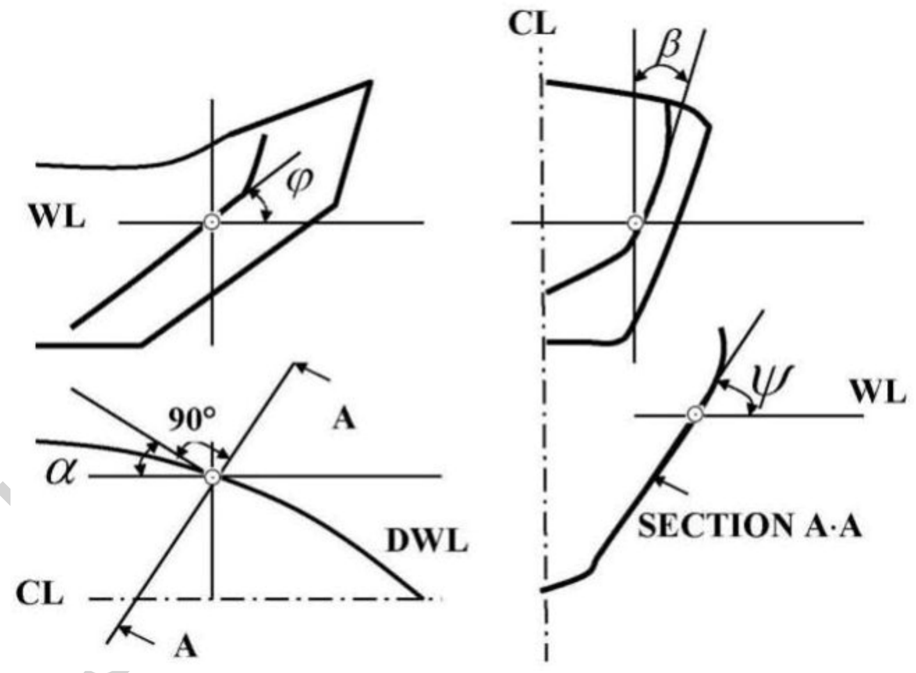

Figure 1. Definition of the hull angles.

The general arrangement of icebreakers and also ice going ships has changed little during the years. The largest change in the arrangement took place in 1970's when the superstructure was changed into deck house i.e. no accommodation was placed in the hull, Figure 2. The reason for the change was partly to increase the height of the bridge to improve the visibility and partly to avoid the noise and vibration caused by ice in the crew accommodation.

Figure 2. Early icebreakers had accommodation in the hull like the first USCGC Mackinaw (left). After 1970's the deck house replaced the superstructure like in the Finnish icebreaker Sisu (right).

Machinery of icebreakers has experienced many changes since the early icebreakers with steam engines and fixed pitch propellers. The economy and torque capability of steam engines was improved much with the introduction of diesel-electric machinery (diesel main engine with generators and electrical propulsion motors). The first diesel-electric icebreaker was the Swedish IB Ymer in 1933. The diesel-electric machinery is more expensive than a direct diesel drive but the torque performance of a fixed pitch propeller with a direct drive is not good; the solution for this is the use of controllable pitch (CP) propellers. These became common in early 1980's in merchant ships. The bow propellers were introduced in icebreakers in the end of 19^{th} century (first European bow propeller icebreaker is the Finnish Sampo). The bow propeller improves the ice breaking capability by reducing the forces required to break ice and by reducing the friction. Only lately the bow propellers have been made superfluous by the introduction of so called Z-drives (azimuthing propulsion units); the first icebreaker with azimuthing propulsion was the Finnish multi-purpose icebreaker Fennica in 1993.

Strength of ship hull and machinery is still mostly designed based on experiences from earlier ships. When damages caused by ice have occurred, strengthening of the structures is indicated. These experiences have been collected into the rules of the classification societies and thus most of the strength design is even nowadays done following the classification society rules. The Baltic is the most active sea area for ice navigation and it is natural that the experiences from Baltic are followed worldwide. The experience from ship damages is reflected in the strength level used in the Finnish-Swedish Ice Class rules. Already these short notes from the historical development of ice design show how closely the design of ice capable ships is linked with the experience from earlier designs. As the collection of feedback is not a straightforward task by any means, those designers that can follow the performance of their design in ice operation have an advantage.

3. Performance in Ice

Ship performance in ice consists of ability to break ice and to maneuver in ice – these capabilities have been defined in the functional specification. The capability of breaking ice is measured in uniform ice conditions (level ice, brash ice) by the speed at which certain ice thickness can be broken. Ice ridges and multi-year ice floes are distinct ice features and the capability in these is measured by the ability to penetrate these. The speed that the ship makes in ice is determined by the ice resistance determined by ice properties, and the hull shape and main dimensions as well as the thrust provided by the propulsion. The maneuvering performance is similarly determined by the transverse forces provided by the rudder(s)/azimuthing thrusters and the resisting forces mainly due to ice. It is thus clear that the performance in ice is influenced by the resisting forces and the propulsive forces and these can be improved (resisting forces minimized and propulsive forces maximized) by hull shape and propulsion design, respectively.

Ice Resistance

Ice resistance refers to the time average of all longitudinal forces due to ice acting on the ship. These ice forces are divided into categories of different origin;

- Breaking forces;
- Submergence forces; and
- Sliding forces.

In different ice conditions the relative importance of these components varies; in level ice the breaking component is usually the largest but in brash ice or in smaller ice floes the other two components become more important. The breaking force is related to the breaking of the ice i.e. to crushing, bending and turning the ice. Submergence is related to pushing ice down along the ship hull whereas the sliding forces include frictional forces. Usually the velocity dependency of the ice resistance is attributed to the last component. A sketch of ice resistance experienced by a ship is shown in Figure 3.

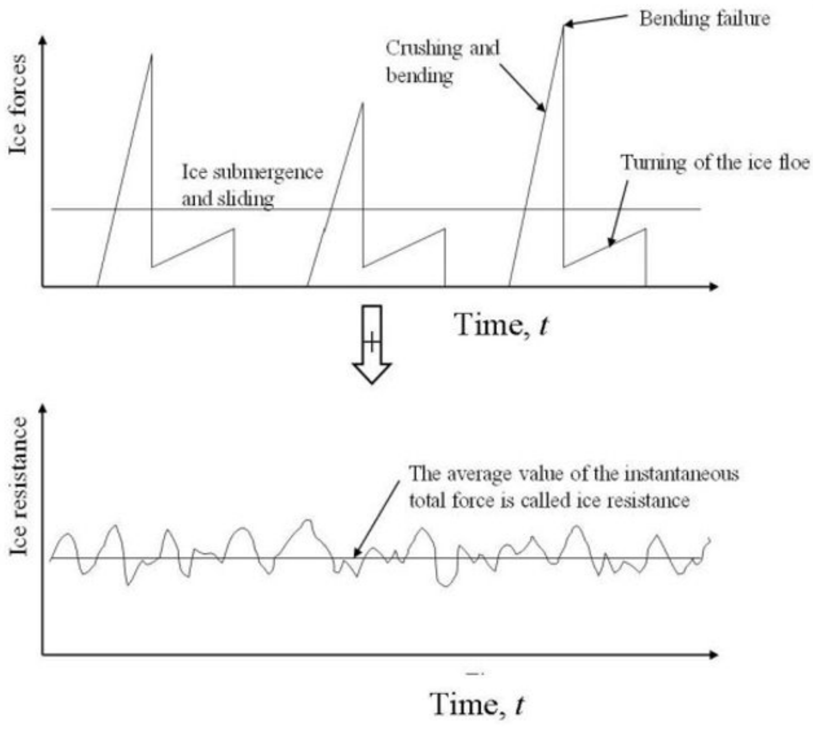

Figure 3. The nature of ice resistance as an average longitudinal force.

Ice resistance in level ice is the basis of all other ice resistance formulations, this is investigated first. If a test is made in uniform level ice where the ship power is kept constant, the ship eventually reaches a constant speed. The total resistance in ice, R_{iTOT}, can be assumed to be equal to the propeller thrust (with so called thrust deduction deducted). If the power is decreased, a new, lower speed is reached and a new ice resistance point can be obtained. These schematic points are shown in Figure 4. When decreasing the power further the point marked C is reached. Here any lower power brings the ship to a stop. If the test is carried out by starting a stopped ship and increasing the power, it is noted that the calculated thrust at the power when the ship starts to move is quite large (point A) and after start the ship accelerates to a speed beyond the point C. The points C to D can be extrapolated to zero speed – this gives the ice resistance at zero speed which is commonly identified with the breaking resistance.

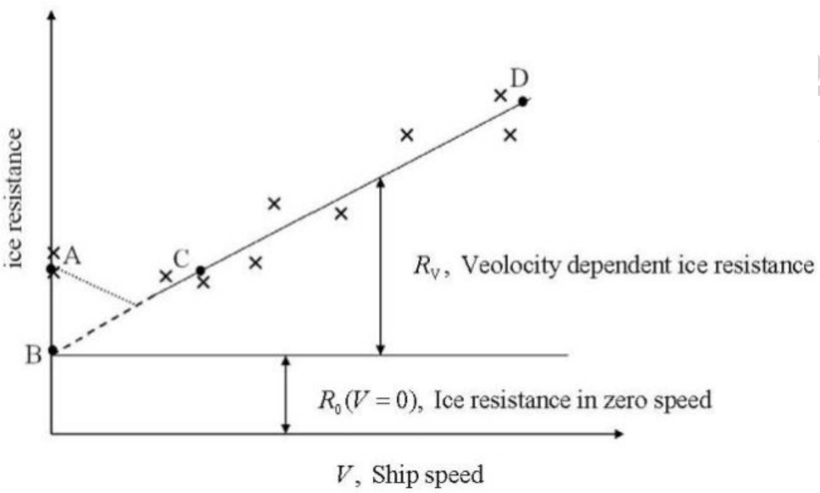

Figure 4. Measured ice resistance points.

The total resistance in ice is assumed to be the sum of the pure ice resistance R_{i} and open water resistance R_{ow}

$$R_{\mathrm{iTOT}} = R_{\mathrm{i}} + R_{\mathrm{ow}},$$

even if this assumption is inaccurate. The total resistance in ice and the open water resistance can be determined experimentally in model tests and then the pure ice resistance can be determined by subtraction. The ice resistance is further divided into components mentioned above, thus the ice resistance is

$$R_{\mathrm{i}} = R_{\mathrm{B}} + R_{\mathrm{S}} + R_{\mathrm{F}},$$

where the components are the breaking, submergence and friction component, respectively. Most methods used to calculate the ice resistance are based on regression on full scale and model scale data. The regression assumes the ice resistance to be linear with ship speed and to consist of these three components, see for example Lindqvist (1989) or Riska et al. (1998). Thus the calculation methods for ice resistance are at best semi-empirical, and these methods should be used cautiously, especially outside the range of validity. The calculation methods to determine the ice resistance should be used only in the conceptual design phase as these methods cannot account for the details of the hull shape. When the design proceeds, ice model tests should be carried out to finalize the hull shape.

The ice resistance in broken ice (brash ice) can be determined similarly as the ice resistance in level ice. The only exception is that the breaking component is different; it exists and is attributed to cohesive forces present in broken ice. Brash ice resistance formulations are presented for example in Riska et al. (1998).

Ice resistance in ridges is dealt with similar methods as in brash ice. The major difference is, however, that as brash ice resistance depends on brash ice thickness H, the ridge resistance depends similarly on the ridge thickness, which is different *at each location along the hull*. Thus the resistance from a ship length segment Δx at the location x (in some suitable fixed coordinate system) is (see Riska et al. 1998)

$$\Delta R_{\mathrm{R}} = R_{\mathrm{R}}(H_{\mathrm{R}}(x)) \cdot \Delta x$$

where $R_{\mathrm{R}}(H_{\mathrm{R}}(x))$ is the ridge resistance in ridge thickness H_{R} *per unit ship length*. Here the ship speed is not mentioned as the ridge resistance is commonly treated as speed independent – and the speed dependency is allocated to the open water resistance. The total resistance in a ridge is thus

$$R_{\mathrm{R,TOT}} = R_{\mathrm{R,B}}(H_{\mathrm{R}}(x_{\mathrm{bow}})) + \int_{L_{\mathrm{PAR}}} R_{\mathrm{R}}(H_{\mathrm{R}}(x)) \cdot dx + R_{\mathrm{ow}}(v)$$

where the $R_{\mathrm{R,B}}$ is the ridge breaking resistance acting at the ship bow. The speed dependency in open water resistance is emphasized. The length of the ship parallel midbody is denoted as L_{PAR}.

As the ship is moving, location of the ridge relative to the ship is changing ($x = x(t)$) and as the ridge is not of uniform thickness, ridge resistance is changing constantly with time. It is consequently more suitable to speak of the energy required to penetrate certain size of ridge. This energy depends on ridge cross sectional area A and ship dimensions, for large tanker the energy has been determined to be about $C \cdot A$ where C is about 1 kJ/m^2 (Riska et al. 2006). A way to determine the ridge resistance and the penetration energy in model tests is shown in Figure 5.

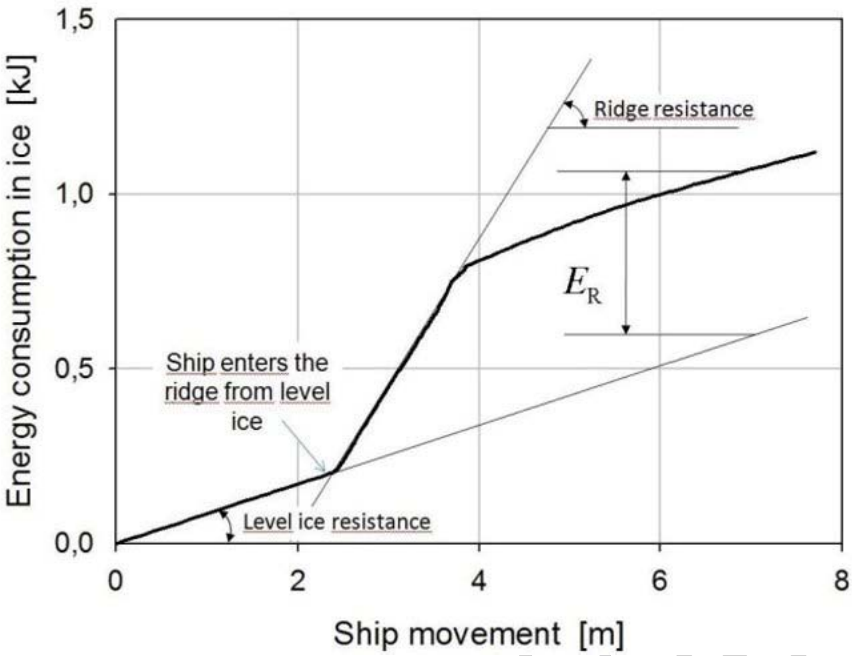

Figure 5. Energy consumed in penetrating ice ridges, E_R, based on ice model tests (Izumiyama & Uto 1995).

Performance in ice

Measures by which the ship performance in ice is described can be seen from the functional specification described above. These measures can include:

- Speed(s) achieved in certain level ice thickness (for example 3 knots in 1.5 m thick ice with a snow cover of 20 cm);
- Penetration of certain size ridges with a stated impact speed (for example a ridge of maximum thickness 8 m penetrated with an initial speed of 10 knots); and
- Ship turn of 180^0 in less than certain time in certain ice thickness.

Ship design proceeds so that at early design phase some analytical methods are applied to determine the level ice performance, ridge penetration and brash ice performance. Some of these methods are described in Riska et al. (1998) and Juva & Riska (2002) but it is difficult to find a comprehensive presentation of methods to be used. The methods presented in references are at best rudimentary and as there are no analytical methods that can be applied in determining the maneuvering performance, ice model tests are necessary at the end of conceptual design phase to verify the design.

Performance in level ice is described with ice thickness versus ship speed $(h_i - v)$ plots. In these plots the speed the ship can reach in specified ice thicknesses at full power is drawn, see Figure 6. In an early design phase the thickness-speed plot can be determined as follows. First the ice resistance curves (ice resistance versus ship speed at different level ice thicknesses) are obtained by some semi-empirical ice resistance formulation or from ice model tests. Next the net thrust concept is used; this is the propeller thrust available to overcome the ice resistance i.e.

$$T_{\mathrm{NET}} = T(1-t) - R_{\mathrm{ow}},$$

where the superposition principle of pure ice resistance and open water resistance R_{ow} is assumed valid, T is the thrust of propeller(s) and t the thrust deduction coefficient. As the propeller thrust, thrust deduction nor open water resistance are available in early design, the expression for net thrust must further be simplified. This is done by using an expression for bollard pull T_{B} and a quadratic factor for the speed dependency as follows

$$T_{NET} = T_B \cdot \left(1 - \frac{1}{3}\frac{v}{v_{\mathrm{ow}}} - \frac{2}{3}\left(\frac{v}{v_{\mathrm{ow}}}\right)^2\right) = K \cdot (P_{\mathrm{D}} \cdot D_{\mathrm{P}})^{2/3} \cdot \left(1 - \frac{1}{3}\frac{v}{v_{\mathrm{ow}}} - \frac{2}{3}\left(\frac{v}{v_{\mathrm{ow}}}\right)^2\right)$$

where v_{ow} is the open water speed of the ship, P_{D} propulsion power, D_{P} propeller diameter and K an empirical factor for bollard pull (for more information of this see Juva & Riska 2002). The values of 0.78 for single screw and 0.98 for double screw ships can be used.

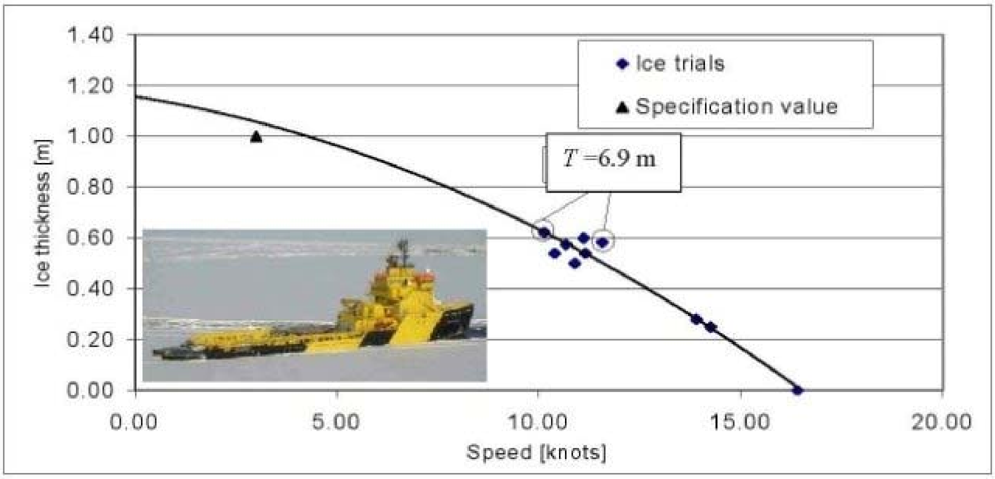

Figure 6. Performance plot for the icebreaker Tor Viking (Riska et al. 2001).

The points where the ice resistance curve at each ice thickness (h_1, h_2 and h_3 in the graph below) intersect with the net thrust curve give the points on the $h_{\mathrm{i}} - v$ plot. In Figure 7 a word of caution is mentioned viz. the net thrust concept assumes no propeller – ice interaction and depending on the propulsion layout, hull lines and ice thickness, this interaction can be severe. Thus designers often make a margin for this interaction. The resistance-net thrust plot and the resulting $h_{\mathrm{i}} - v$ plot are shown for the USCGC Mackinaw in Figure 8. The ship performance in old navigation channels (brash ice) is determined similarly as in level ice, only resistance formulation used is different, see Riska et al. (1998).

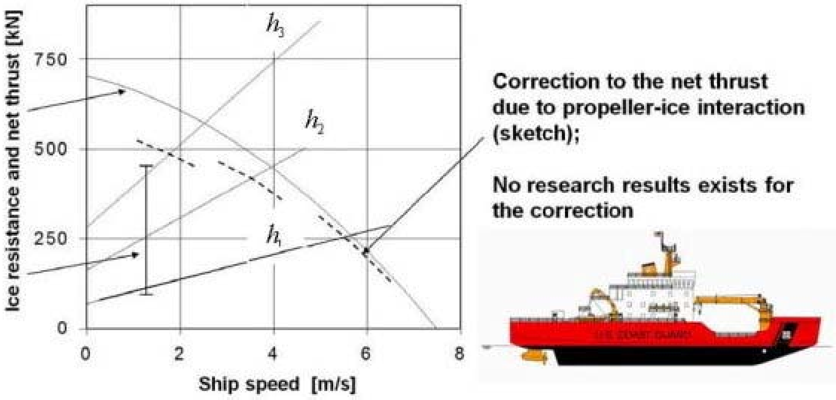

Figure 7. Ice resistance curves for different level ice thicknesses and the net thrust curve for USCGC Mackinaw.

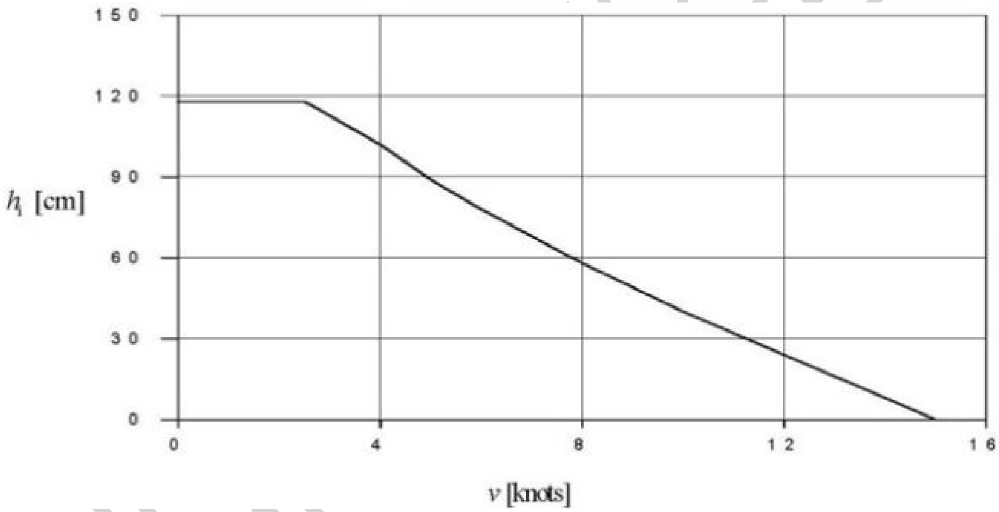

Figure 8. Resulting $(h_i - v)$ curve from Figure 7 for USCGC Mackinaw.

Turning performance in ice is measured by the diameter of the turning circle (divided by the ship length). Turning diameters for two icebreakers are shown in Figure 9. The requirement for escort icebreakers and other ships that have to maneuver well in ice is that the turning circle diameter should be less than 5L. The turning ability measured by the turning circle diameter is not the only measure for maneuvering capability of an icebreaker. Important is to perform certain maneuvers in shortest time possible. This maneuvering performance often includes different escort maneuvers that icebreakers commonly do, see Figure 10. A good maneuvering capability can be achieved by a proper hull form design, having a large rate of turn of the rudders/azimuthing thrusters and providing a large transverse force. It is thus clear that azimuthing thrusters provide a maneuvering ability that cannot be surpassed with other turning means.

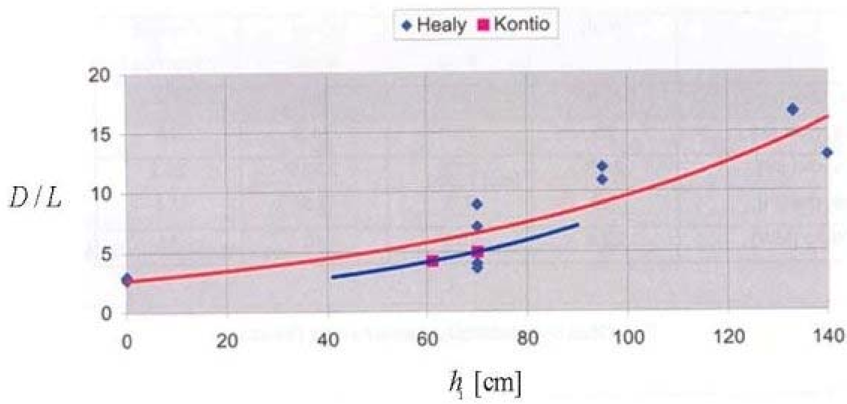

Figure 9. Turning circle diameter *D* of two icebreakers divided by the ship length *L* in different level ice thicknesses (Hänninen & Riska 2001)

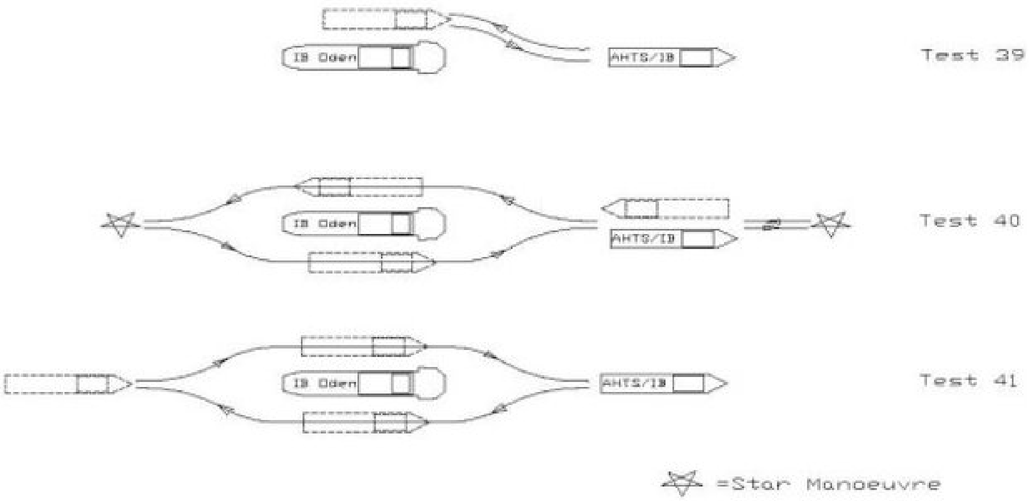

Figure 10. Three different maneuvers performed when the escorted ship is stuck in ice. These maneuvers were performed in the full scale trials of the icebreaker Tor Viking and times for each operation were 13' 47", 17'20" and 17'40" for tests 39, 40 and 41, respectively (Riska et al. 2001).

Ship performance in ridges is not measured by ridge resistance or any speed reached in ridges as commonly the largest ridges cause a resistance, even defined as an average value as in Figure 5, that is so large that the delivered thrust cannot overcome it. Ridges are penetrated by consuming the kinetic energy of the vessel; thus the correct parameter for ridge capability is the energy required to penetrate ice ridges. This depends on ship displacement, ship main dimensions and on bow shape, see Riska et al. (1998).

Hull Shape Design

The hull shape design of ice breaking ships aims at:

- Minimizing the ice resistance by selecting optimal beam and bow shape;
- Ensuring good operational (maneuvering) characteristics;

- Enabling the ship to go astern as much and as well as the operational description requires; and
- Ensuring a proper undisturbed operation of the propeller(s) by minimizing the amount of ice impacting on the propeller(s).

The most important parameters for ice resistance are the beam B and the stem angle φ. Large beam causes more resistance and thus narrower ships with a large L/B ratio (especially if there is a draught restriction) is the result. For an icebreaker small beam is not, however, good as the escorted ships should get as wide channel as possible. Typical largest icebreaker beams at present are about 26 m. A smaller stem angle induces larger bending force while keeping the horizontal force component smaller, thus ice breaking ships have quite small stem angles, 20^{o} to 25^{o} is common. Nowadays also the stem is rounded as this decreases the crushing at the stem, Figure 11.

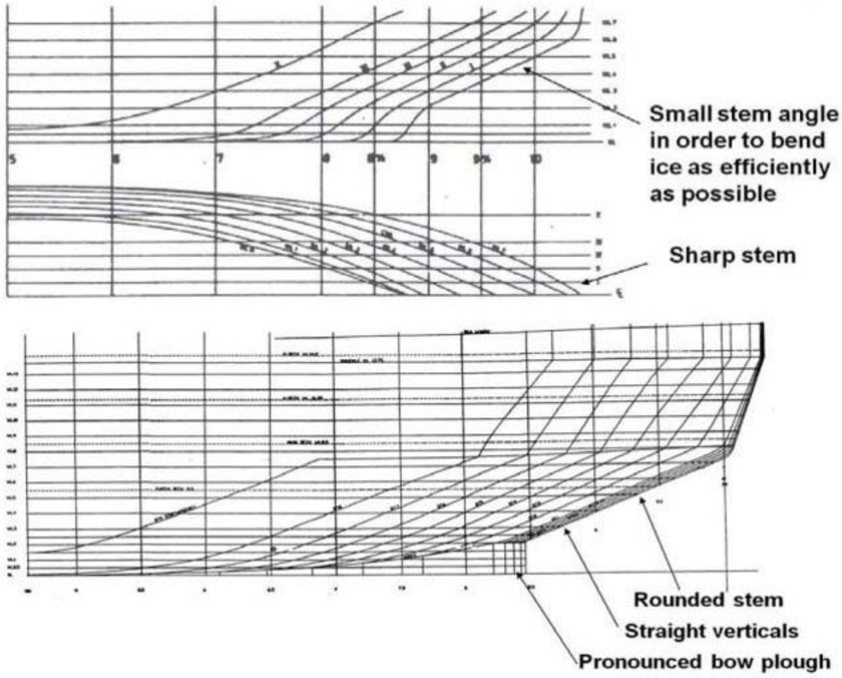

Figure 11. Classical ice breaking bow shape (top) and modern icebreaker (bottom).

Maneuvering characteristics are improved if the transverse force is large (large rudders). This has led to using azimuthing thrusters (more of these below). From the hull shape perspective, the stern shoulder area is crucial for good maneuvering characteristics. If the stern shoulders break ice in bending, the ship turns better as the resisting force for turning is this way minimized.

The performance astern is important if the ship has to navigate independently. When encountering ridges, the ships often get stopped and in order to be able to proceed, the ship must be able to back and ram again (or after going astern go around the ridge). Good backing performance is reached by avoiding blunt lines at the stern. Many merchant ships that are only ice strengthened need not go astern in ice but can count on icebreaker escort in heavier ice conditions. In this case the design of the stern shape is less important.

The propellers encounter those ice floes that have made their way under the ship (flat) bottom. Propeller-ice interaction threatens the integrity of the propulsion but also decreases the propulsion efficiency; generally the required torque is increased while the produced thrust is decreased if much ice interacts with the propeller. Hull shape influences the amount of ice that gets under the ship bottom and consequently impacts on the propeller(s). Bow shape should be such that it allows the ice floes to float towards the surface before getting under the bottom. One way to do this is to make a bow plough, see Figure 11. When the ice floes follow the buttock lines, they hit the bow plough that pushes the floes aside. There is an ice thickness limit up to which the bow plough is efficient, thicker ice will go under the bottom. The disadvantage of the bow plough is that it increases somewhat the ice resistance and also the open water resistance – in ships that are required to do heavy ice breaking the advantages outrank the disadvantages of a bow plough.

There are several points that should be checked in finalizing the hull lines for good ice breaking performance. At present there is no alternative to ice model testing as analytical methods are not so advanced that they could predict the effects which can be deemed local. The operation of the bow plough in deviating ice has already been mentioned. Here two other effects are mentioned. The first one concerns the bulbous bow. It has often been stated – and this has been reflected in some classification society ice rules – that bulbous bow is not good in an ice going ship. This is because the bulb itself does not break ice very well and also because there is one frame that is vertical at the bow, if the ship has a bulbous bow (at the bulb ice is bent up and at the shoulders down; thus there is a vertical frame in between).

Present experience shows that most merchant ships need not break ice as they either sail in broken channels or follow an icebreaker. Thus ice strengthened ships often have bulbous bow which is not a handicap in broken ice. The reason for this is that broken ice is displaced around the hull in a way that resembles the hydrodynamic flow, see Figure 12. Only in ice going ships and icebreakers which must break ice themselves the bulbous bow is not appropriate. By shaping the bulbous bow for ice, much of the additional ice resistance can be avoided. An ice bulb is shown in Figure 13.

Figure 12. Bow wave created in a brash ice channel in front of a ship having a bulbous bow.

Figure 13. A ship having an ice bulb, circled in the figure (www.nesteoil.com).

The other necessary check in hull lines is the presence of so called shoulder crushing. This phenomenon is created if the bow breaks in bending a narrower channel than the ship beam. In this case the ship has to force herself into a narrow channel by crushing the rest of the channel width close to the maximum beam (forward shoulders). The crushed ice extruded on top of the ice indicating the presence of shoulder crushing is shown in Figure 14. If shoulder crushing is present, the ice resistance is increased much and it can even lead to a hull shape that is considered a failure. The only way at present to detect this phenomenon is to conduct ice model tests. In these the visual observation of the breaking is the best way to detect shoulder crushing – especially as the present model ices are somewhat weak in comparison with the bending strength. Thus the shoulder crushing is not revealed as a much increased ice resistance in ice model tests. There are simulation tools under development (Su et al. 2009) which may be able to predict the crushing. These simulate the breaking pattern assuming a certain size and shape of the broken ice floe. The first results of these are encouraging as Figure 15. shows.

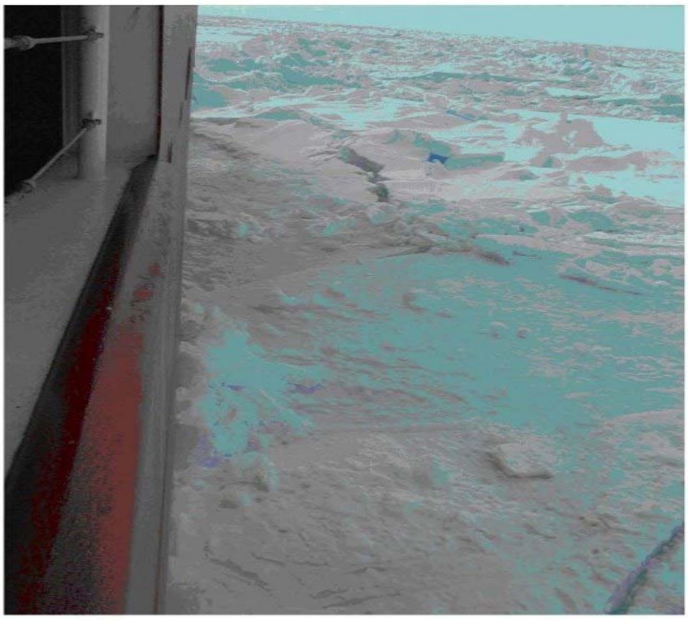

Figure 14. Shoulder crushing at the bow of an icebreaker. The image is taken looking forward.

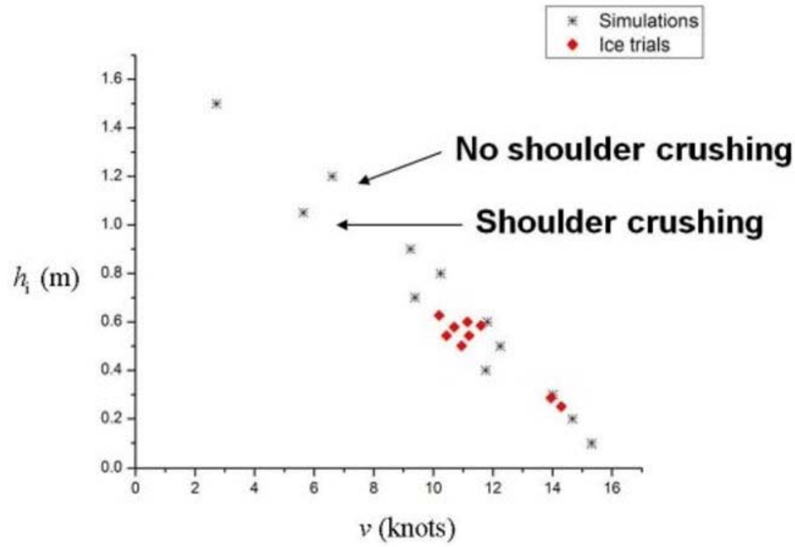

Figure 15. Observed and simulated points of the $h_i - v$ plot for the Swedish icebreaker Tor Viking and the simulated breaking pattern. Measured points are from Riska & al (2001) and simulated from Su et al. (2009).

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Biographical Sketch

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