SHIP – ICE INTERACTION IN SHIP DESIGN: THEORY AND PRACTICE

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Contents

Summary

There are three aims for this chapter; First, to categorize different ice types encountered by ships in cold regions, second, to describe different scenarios in an ice field a ship may experience and third, to present estimates of ice forces under different scenarios. This chapter serves to set the foundation for ship design for ice covered seas. When designing a ship, the function of which is to operate in ice conditions, the designer needs knowledge of how ice is acting on the ship and how this interaction is modeled. The starting point of ship design is the description of what the ship must do. This is called functional specification and it describes the task of the ship and her performance – also in ice. Thus the design basis for ice capable ships is made by a description of ice conditions and other environmental factors pertaining to design. Further, the ship function must be defined and in order to gain insight of the functional requirements, a short description about the operational environment of ice capable ships is given. The ice action on ship or rather the ship-ice interaction (as when ship and an ice feature are in contact, the contact force depends on the response of the ship and ice) occurs in very many different forms. In order to aid the design, these interaction cases are usually categorized into some major ones highlighting the major forces and other ice actions. These are described in such depth that is suitable in gaining a qualitative understanding about ice action on ships. This chapter is followed by a description of the major design features that are based on an understanding of the ice action.

1. Introduction

Ship design begins with defining of the tasks that the ship must perform. These tasks include the required operation, such as dredging, towing or transporting certain types of goods, the intended operational area for example Beaufort Sea or Kara Sea, and the required operational performance, such as extended summer operation in the Beaufort Sea or year-round in the northern Baltic. These requirements are stated in the functional specification of the ship that is developed by – and sometimes for – the ship owner. The size of the ship (displacement and deadweight i.e. payload and consumables) and other main particulars like machinery arrangement follow after the functional requirements are specified. The amount of transported cargo and the work the ship must perform together with the required speed, equipment, accommodation and operational periods determine, within limits of rules and regulations, these main particulars.

If the ship is to operate in ice, this must be taken into account in the early design phase. Design for ice capability influences all the ship characteristics: the hull shape and main dimensions, hull strength, machinery and equipment. If the requirements on ice capability are not very high because the operation is limited to thin ice conditions or occasional entry during early winter in ice covered waters, then it is sufficient to design the hull shape based on open water performance and in strength issues follow rules of classification societies or other regulatory bodies. Design of ship hulls intended for heavy ice conditions and regular traffic in ice is based on taking the ice action more explicitly into account. Even these ice going ships of high ice performance can be designed based on rules but sometimes a direct approach to design is used. This direct approach to design is started by defining the ice conditions and is then followed by estimating the adequate performance and strength in ice based directly on the defined ice conditions.

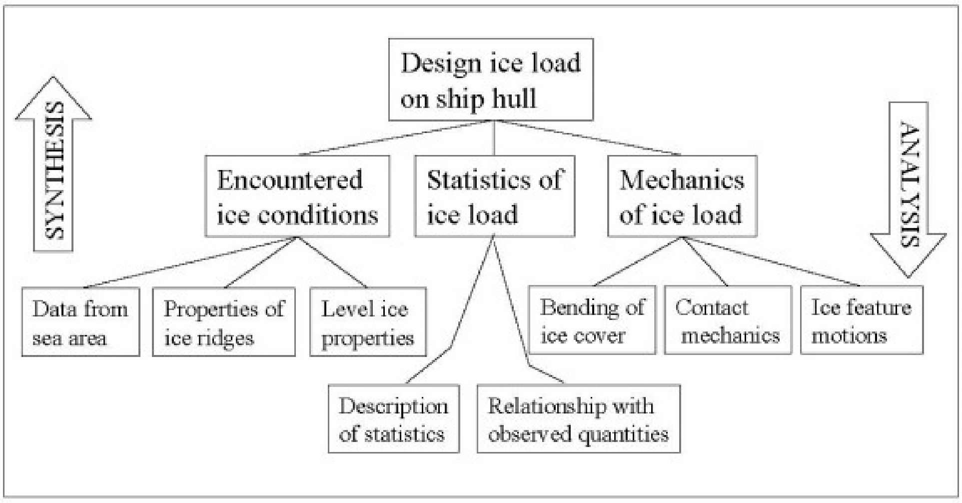

Figure 1. The constituents of determining the ship hull ice loading for design.

The direct design requires quantitative knowledge of the ice conditions in the operational area, in a form that can be used in designing the ship performance and strength. It also requires a quantitative description of the intended ship operations. This broad knowledge base required in direct design of the ship hull is illustrated in Fig. 1. In principle all factors influencing the final design must be known, especially when following a direct design path. This is impossible in practice and thus the actual design at best is a mixture of direct and conventional methods. Conventional design is based on knowledge from earlier designs. Ice model tests are also conducted for ships that will perform ice breaking tasks. Ice model testing is used to finalize the hull shape design and also check the propulsion requirement.

The design for ice capability includes three aspects: firstly the ship structures must have an adequate strength, secondly the performance of the ship in ice must meet the functional requirements and thirdly the ship systems and equipment must function in the temperatures (or more generally - climate) encountered in the operational area. The ship hull and hull girder must be strong enough under the ice loading. The propulsion machinery and propeller shaft line must also have adequate strength to withstand the ice impacts. Strength design includes also checking for the fatigue strength, even though the ice-induced fatigue has not been a major problem for ice capable ships. Finally, structural design for ice includes checking on the vibration response to ice loading and noise transmission. The vibratory and noise response are different from those in open water conditions as the excitation in ice comes mostly from the bow which experiences the ice impacts.

The performance of an ice capable ship is evaluated by its forward speed under the design ice conditions. For many ships the speed astern is also a design feature as ships that are stopped by ice must go astern in order to either ram again or deviate from the direct route in search of easier ice conditions. An ice capable ship also needs to meet the requirement for the machinery to provide the required propulsion thrust in ice. These stated requirements influence the hull shape design and machinery design. Furthermore, in order to ease the operation in an ice field for the crew, the bridge design needs special attention for clear visibility to ship sides and astern.

The ship’s systems and equipment must be able to function in cold temperatures. This requirement applies to deck equipment, such as mooring winches, cranes, and cargo hatches, and to navigation and emergency equipment, such as life boats and fire fighting equipment. Operation in cold weather places also requirements for the general arrangement, especially for areas and spaces that are exposed to icing, snow and rain. Bridge, mooring equipment and lifting apparatus must be designed to guarantee adequate visibility. The construction materials for the ship hull and for all the exposed equipment must have proper strength and integrity in low temperatures. Common problems such as the brittleness of materials under low temperatures must be overcome.

In this chapter the major ice induced challenges on ship design are described. The actual design of ice capable ships will be the topic of the next chapter. The description in this chapter is qualitative and more formal physical description using the exact mathematical formulation is not given, with the exception of two cases. First is the description of the ice forces in general and second is to show a more detailed example how to calculate the ice force. These two cases serve the purpose of illustrating the main difficulties in determining the ice loads and also the effect of dominant parameters.

2. Ice and Weather Conditions

The description of the ice conditions in a way that is usable in ship design differs from the geophysical way of describing ice. Thus it is instructive to see how a ship designer views the ice conditions. The ice covered seas are located mostly in the high northern or southern latitudes (Arctic and Antarctic) where the temperatures are low and also the daylight hours are short in winter. Sea ice can, however, be found in surprisingly low latitudes like the Caspian Sea, Sea of Azov and the Bohai Bay. The main weather parameters that form the design basis for ships include:

- Description of ice cover;
- Sea and air temperatures;
- Winter or rather ice season lengths.

The natural ice cover is commonly dynamic because of the driving forces that are caused by the drag of the winds or currents. The driving forces break the ice cover, create leads when the ice field is diverging or ice rafting and ridging when the ice field is converging. Thus ships navigating in the middle of the sea basins very seldom encounter level ice. The ice ridges constitute the largest obstacle for shipping as even smaller ice ridges stop a merchant vessel. The ice ridges have a triangular or trapezoidal cross section, the largest ridges being about 30 m thick. A typical sea ice field is thus composed of some portion of level ice and open water with ice ridges scattered among the relatively level ice. Fig. 2 shows typical sceneries from a first year ice sea area – Fig. 2a is from the most northern Baltic, the Bothnian Bay, where strong winds often produce an immobile ice field. Fig. 2b is from the Gulf of Finland where the ice coverage is less than 100 % and the ice cover is more mobile.

Figure 2a. A heavily ridged ice field in the northern Baltic.

Figure 2b. More open sea ice cover with ice ridges, level ice areas and open water patches, a view from the Gulf of Finland.

The ice motion creates different zones of ice. Close to the shore is the fast ice zone where ice is not broken and stays stationary due to the support of the outer islands or a grounded ridge zone. In some coastlines this zone is extensive (for example the Pechora Sea in Russia) but in steep coastlines without islands, this zone may be negligible (like north-eastern coast of Sakhalin). Outside of the fast ice zone ice cover is broken and moving. The zone where the effect of the coastline is felt is called the transition zone. Examples of this kind of seas are the Beaufort Sea (Beaufort Sea gyro pushes ice against the northern coast of Alaska) and northernmost Baltic (westerly winds push ice against the Finnish coastline).

In those transition zones where ice cover is often converging, the ice coverage tends to be 100 % with heavy ridging. If the ice is diverging in the transition zone (like in many Antarctic seas) the coverage tends to be less and ridging less intense. The ridge size in the transition zone is stochastic. The statistics of ridges has been studied much and most often it is concluded that the ridge size (and density) follow an exponential probability distributions.

Finally, outside the transition zone is the pack ice zone. Some scientists state that the only pure pack ice zone is formed in the Arctic Pack – it is however difficult to see the difference between the transition zone and the pack ice zone and anyhow this difference does not matter for ship design. These different ice zones are illustrated in Fig. 3.

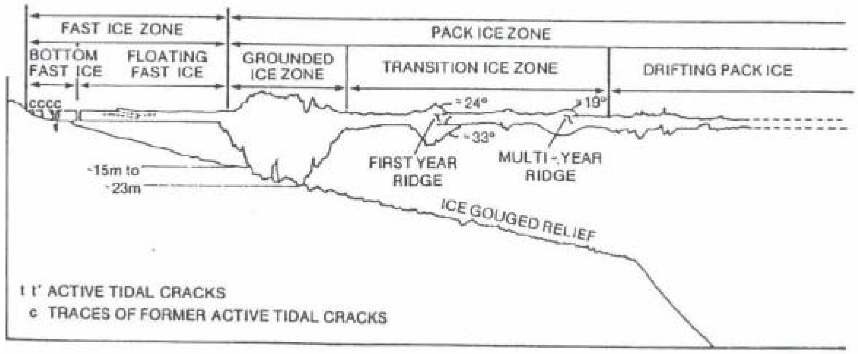

Figure 3. The ice zones in a sea ice cover (Icex 1979).

<u>Ice parameters</u>

A ship sailing through a natural first year ice cover encounters thus level ice, open water and also penetrates ice ridges. The description of ship transit through this kind of ice cover requires the following data:

Coverage of ice	C	Portion of sea surface covered by ice (given usually in tenths of ice area relative to the total area);
Level ice thickness	h_i	If there are several different thicknesses, these are given versus the coverage of each thickness;
Average maximum thickness of ice ridges	H_R	This thickness usually ignores the part above water which is called sail;
Density of ridges	μ	Number of ridge sails along a straight route segment (in units of ridges/km).

Typical ice coverage in stationary ice cover is about 90% and maximum level ice thickness typically in first year ice areas is 1 m (Baltic) and 2 m in the Arctic. Average ridge thickness in the Baltic is about 5 m whereas the ridge density varies from 4 to 10 ridges/km. If the average ridge thickness is more than 10 m, the ice conditions can be considered severe.

The most important single ice parameter for ship design is, however, the existence of multi-year ice. For many sea areas it is clear that multi-year ice does not exist at all as all ice melts during the summer (Baltic, Okhotsk Sea, northern Caspian Sea, Sea of Azov, St. Lawrence Seaway) and in some other areas it is clear that multi-year ice must be reckoned with (Beaufort Sea, Baffin Bay, Russian eastern Arctic seas like the Laptev Sea).

If ice survives the summer melting season, multi-year (MY) ice is created. When level ice starts to melt during summer, the salt (brine) present in the ice cover drains into the sea water while the ice mostly melts on the surface forming melt ponds. When temperatures turn cold again, ice starts to freeze from the bottom. This cycle of freezing and melting quickly reaches an equilibrium thickness for multi-year ice at about 1.8 to 2.5 m. Only a few cycles are required to reach the equilibrium, and it has been stated that no layer in MY ice is older than about 20 years. When a first year ridge survives the summer melt, the voids in the ridge get filled with fresh water and the sail melts. This produces slightly wavelike top and bottom surfaces – and quite uniform thickness, typically somewhat in excess of 5 m. These multi-year ridges can be quite large in horizontal extents, several hundred meters across.

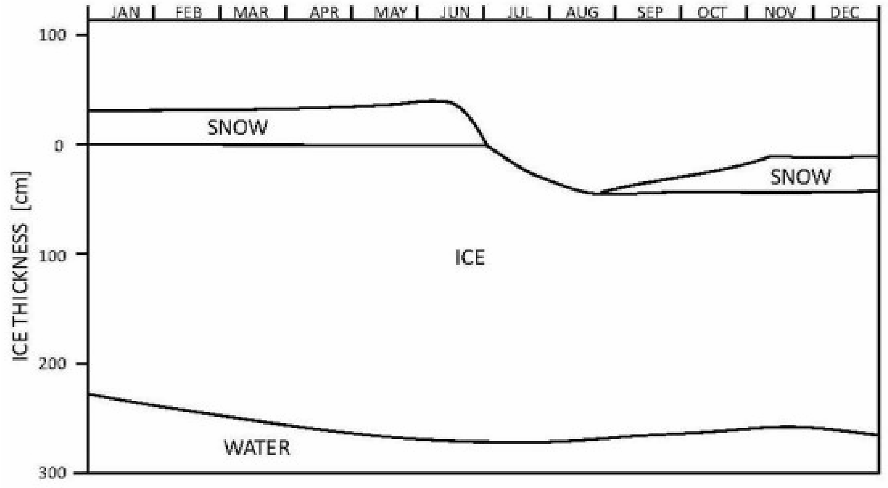

Figure 4. Calculated example of the equilibrium cycle for Arctic sea ice (after Maykut & Untersteiner 1971). The thickness is not corrected for hydrostatics.

The requirements for ice performance given in the functional specification include usually the maximum level ice thickness where the ship can proceed continuously. As the ice resistance in level ice fluctuates in time based on the ice breaking pattern (more about this later), ships cannot maintain a very low speed continuously but get stopped when the ice resistance experiences a local peak. The limiting ice breaking thickness is given as the thickness where the ship can keep a continuous speed; usually a three knots speed on average is used as the minimum possible continuous speed – and the ship performance requirement is defined accordingly, for example it may be required that the ship makes 3 knots in 1.5 m thick level ice. Often, however, this requirement is supplemented with a requirement of higher speed in somewhat thinner ice, for example 8 knots in 80 cm thick ice.

As even the average size ridges cause a high resistance, higher than the ship thrust, ships must penetrate ridges by using their inertia. The capability of ridge penetration can be given as a requirement (certain size of ridge should be penetrated with one ram having a certain initial speed). The level ice performance is easy to verify in full scale and thus ridge penetration and level ice performance are sometimes coupled by using the so called equivalent level ice thickness. In the simplest terms, this is the average thickness of all ice in the area. Assuming ridges to be of triangular cross section with a 25^{o} base angle, an equation for the equivalent ice thickness, in terms of the quantities described above, can be derived from the ice cover cross section as

$$H_{\mathrm{eq}} = \left(C - 4.28 \cdot \mu \cdot H_{\mathrm{R}}\right) \cdot h_{\mathrm{i}} + 2.14 \cdot \mu \cdot H_{\mathrm{R}}^{2} .$$

This equivalent ice thickness is used to describe the ship performance in the general ice conditions where the ridges are smaller than those that would stop the vessel.

The snow cover on top of the ice has an effect on ship performance but not noticeably on the ice loads. The reason for this is that snow influences the frictional forces. If the ship bow is very flat, as it often is for ships with good ice breaking performance, the effect of snow is amplified. There are no rigorous ways to take the snow cover into account and the present common practice in level ice performance descriptions is to use an equivalent level ice thickness, h_{eq}. This is obtained from the level ice thickness h_i and the snow thickness h_s as

$$h_{eq} = h_i + \kappa \cdot h_s ,$$

where the coefficient κ is commonly set at about 1/3.

Icing

Low temperatures must be taken into account in ship design; temperatures in higher Arctic can often be close to -40^{o}C, see Fig. 5. Low temperature influences the construction materials and also poses requirements for deck machinery, accommodation and main machinery. Typical requirement is that the ship must be able to operate in a temperature of -35^{o}C. Here the temperature should be defined carefully as many temperature definitions, especially what comes to the definition of the average, exist. The average temperature in Fig. 5 represents the daily average temperature averaged first over the stated month and then over the year range. The sea water temperature is needed in defining the ship cooling systems, commonly -2^{o}C is used.

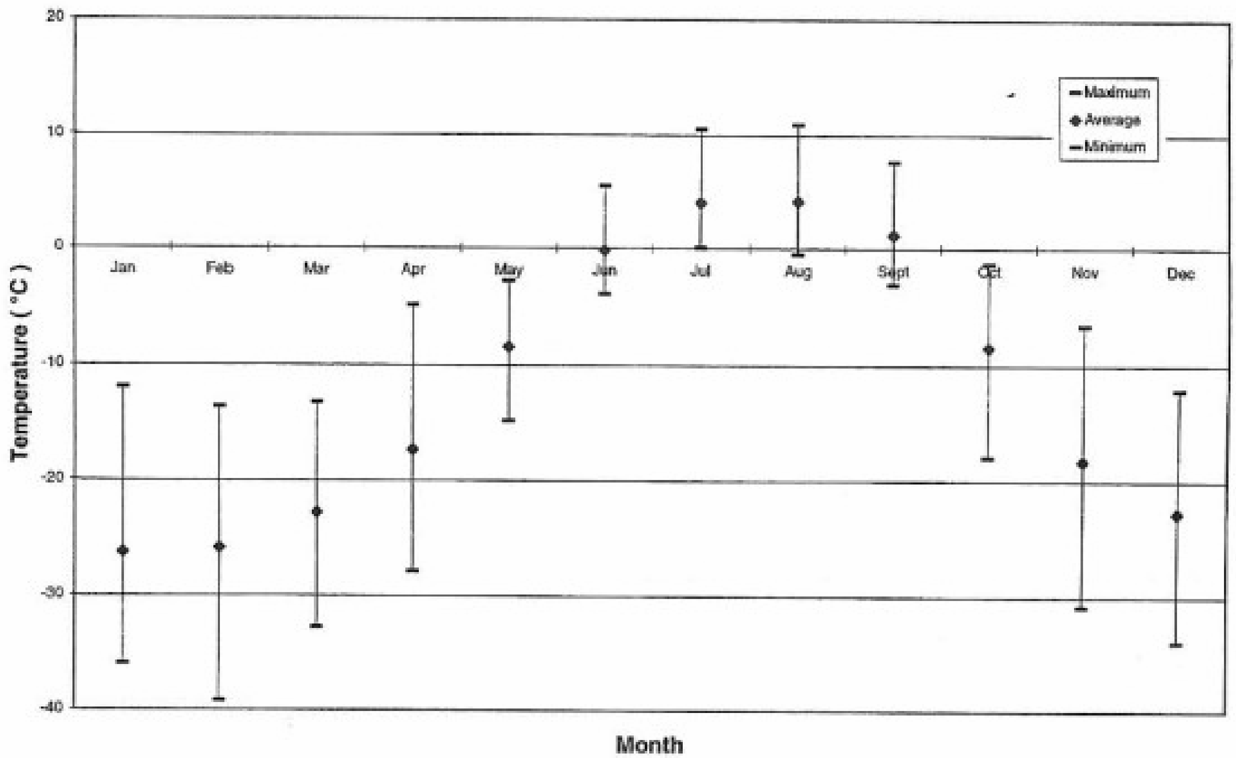

Figure 5. An example of the annual temperature range in the Arctic areas (Kennedy & Patey 1997).

In low temperatures when there is no ice cover, the sea spray can freeze on decks and superstructure as Fig. 6 shows. The spray is generated by the ship bow wave and slamming, and it is blown onboard by the wind. Thus the wind direction ±45^o from the forward direction causes most intense icing. Operational measures like changing course or speed are best ways in avoiding icing but also proper design reduces the icing.

Figure 6. Icing on the deck of a tanker (photo Mari Hoikkala).

The visibility is often restricted in ice covered seas. Reduced visibility can be caused by rain, snow or fog. In high latitudes also the daily period during the winter when sun is above horizon is limited and most of the operations must be performed under darkness. Measures to improve visibility are particularly important in designing the ship's bridge. Fig. 7a shows operation under darkness and Fig. 7b shows the day light hours in three northern locations.

Figure 7a. Icebreaker operating in ice under darkness.

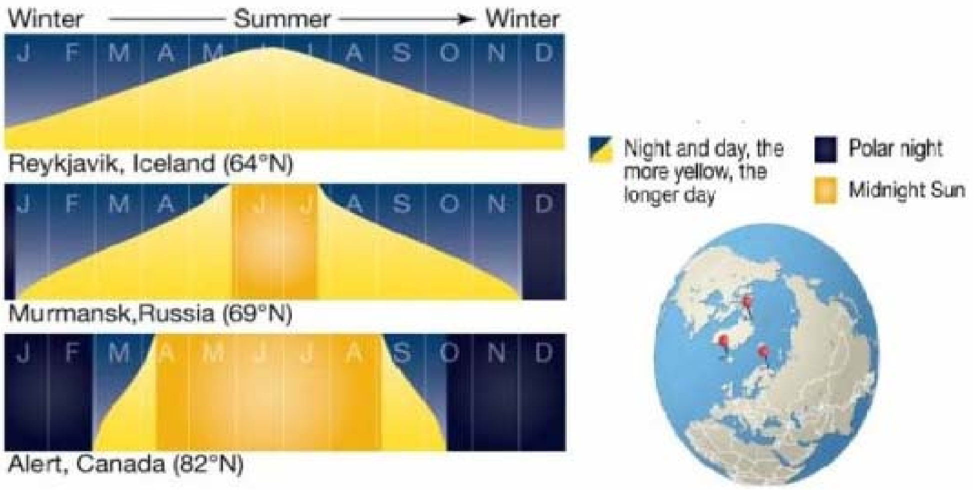

Figure 7b. Day light hours in northern locations Grid Arendal (www.maps.grida.no).

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Biographical Sketch

Kaj A. Riska graduated from the Helsinki University of Technology in Naval Architecture as MSc. in 1978 and DSc. in 1988. He worked at the Technical Research Centre of Finland 1977 – 1988 as the group leader for Arctic Marine Technology. 1989-1991 he was a senior researcher for the Academy of Finland. 1992-1995 he was the director of Arctic Offshore Research Centre and 1995-2005 professor of Arctic Marine Technology at the Helsinki University of Technology. Since 2005 he has been the partner of the company ILS Oy and since 2006 Professor at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. He and his PhD students are investigating the models to describe the ice action on ships and their application in various ship design aspects.