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TURNING IN ICE BY THE CAPTAIN'S MANOEUVRE

Sazonov K.E.
Krylov Shipbuilding Research Institute
St.Petersburg, Russia

ABSTRACT

Ships can turn in ice making either a turning circle or the so-called captain's manoeuvre. However, ice service experience indicates that ships are most often handled with the help of the captain's manoeuvre, otherwise known as "star" or "herringbone" turns. Its main advantage is that it requires only a limited water area, and if the ice thickness is close to critical for the given ship, this manoeuvre may be the only available way to turn. In spite of the fact that this ship turning technique is so often applied in service, it has not yet been described theoretically. This paper presents an attempt of theoretical description of the captain's manoeuvre in ice and suggests an algorithm for computing the size of the water area necessary to perform the captain's manoeuvre.

1 INTRODUCTION

Ice manoeuvrability is a crucial quality for any ice-going vessel. Especially high requirements in this respect have been till recently set to icebreakers intended for convoy escort missions. Today, due to the need for gas and oil export from ice-covered offshore production sites, such design specifications are more and more often extended to ice-going cargo vessels. A key element of any such transportation system is loading gas or oil to tankers in ice, as well as supplying offshore platforms with various relevant items brought by special ships. These roles require such vessels to be able to dock to ice resistant production platforms or storage terminals under any weather conditions, and therefore make it necessary for them ships to have high ice manoeuvrability qualities.

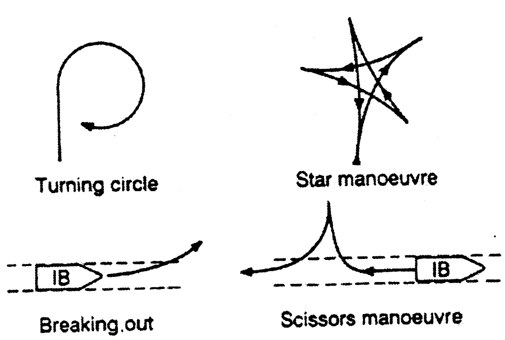

Fig. 1
Manoeuvering methods in ice

In (Lindroos, 1990) they have suggested a classification of simple evolutions available for turning in ice (see Fig.1): turning circle, captain's manoeuvre, bow or stern wedging into lead edges. The latter two may be regarded as variations of the captain's manoeuvre when the ship path pattern has only one apex.

Ice turning circle manoeuvres have been discussed in many publications. Virtually all sea trials of ice class ships include tests for circulation parameters. A summary of such data is available in (Keinonen at al, 1991). Similar detailed studies are carried out in model basins (ITTC, 1996). There are also some publications on mathematical models for ship hull ice forces and moments associated with arbitrary curvilinear motions in ice (Lindstrom, 1990a; Sazonov, 1998a). They have served to develop methods for computing ice turning

circle parameters (Lindstrom, 1990b; Sazonov, 1998b). All these developments enable to predict ice manoeuvrability characteristics already at the design phase.
The situation with the captain's manoeuver is, however, different. In spite of the fact that this manoeuvre is so often used for turning in ice, there is still no proper theory to describe it. Today one can find only scarce full-scale data on time requirements for making the captain's manoeuvre. This paper is an attempt of theoretical analysis of this ship handling technique.

2 THE CAPTAIN'S MANOEUVRE DESCRIPTION

Unlike the turning circle which is achieved by steering to one side without changing engine settings, the captain's manoeuvre requires a sequence of control actions, including wedging with the bow and/or with the stern into the edge of the ice channel. That is done by reversing propellers and tilting the rudder. The captain's manoeuvre is usually described through the following parameters: the water area necessary to execute the turn and the number of ice edge wedgings. Captain's manoeuvre parameters depend on turnability characteristics of the ship and on inertia and manoeuvrability of her propulsion plant. Another crucial aspect which largely governs turning parameters though is least suitable for technical formulations is the skill of the skipper. The great number of involved independent variables which define the captain's manoeuvre makes it quite difficult for theoretical analysis.
A typical technique for tackling such problems is to split them in a series of less demanding tasks. Each of these component simple problems may be, considering its own large number of independent variables, resolved by searching for a certain optimum. E.g., with specified external conditions one may look for the least number of wedgings into the ice edges or, if that number is specified, for the least water area required to turn the ship.
Mathematical models of the captain's manoeuvre should enable to compute the number of wedgings under these or other conditions and to find the required water area. Mathematical models were generated under the following major assumptions:
- the manoeuvre is executed with a constant engine power; for the sake of a better certainty that is assumed to be the maximum power;
- the manoeuvre is executed with a constant rudder angle, i.e. with its maximum possible setting $(\delta=35°)$;
- the additional moment which can be gained on multishaft ships by setting outward propellers to opposite directions is not considered.
Under these assumptions there is a definite relation between circulation ahead/astern speed of the ship and the associated tolerable ice thickness. There is a similar definite relation between the steady turning circle diameter and the ice thickness (ship speed). These functions established with the help of methods described in (Lindstrom, 1990a, 1990b; Sazonov, 1998a, 1998b). serve as inputs for mathematical models. It is assumed that the instantaneous turning circle radius for the captain's manoeuvre in ice satisfies $R_C=f(h_I)$ or $R_C=f(V_S)$. In order to apply these models for finding the time required to execute the manoeuvre, it is also necessary to know manoeuvring characteristics of the ship propulsion plant.

3 THE WEDGING ABILITY CRITERION

Evaluations of typical ship paths associated with the captain's manoeuvre (Fig.1) indicate that the key element of this manoeuvre is wedging into the ice edge. Therefore, the criterion indicating whether a ship can execute the captain's manoeuvre should be the wedging ability condition. This condition will be formulated below.

In order to judge about the ability to wedge into ice edges, it is necessary to solve a set of equations describing horizontal-plane unsteady motions of the subject ship. This task also requires applying a differential model for ice forces, including a scenario of ice failure inflicted by the hull (Sazonov, 1998a). A general-case solution, considering the involved nonlinearity of differential equations, can be obtained only numerically. Since such solutions are very inconvenient for the purposes of mathematical model generation, it was chosen to derive a more simplistic criterion. This criterion is based on observations showing that ships most often "bounce" off the ice edge at the first contact it. The wedging ability criterion may be formulated on the grounds of this observation as follows.

A ship wedges into the side of the lead edge while sailing ahead or astern if the total turning moment generated by her control surfaces and combined with the inertia moment exceeds the maximum resistance due to breaking two ice segments in way of bow and stern extremities. In mathematical terms this condition (see Annex A for detailed derivation explanations) is:

$$F_R > 0.39 ctgb' s_f h^2 \frac{l_I}{l_R} \tag{1}$$

where F_R; l_R is the rudder force and its arm; l_I = $(x\cos\alpha - y\sin\alpha)$- is the ice force arm; x and y are coordinates of the point at which the ship comes in contact with the ice edge; α is the waterline angle at the subject contact point; β is the hull slope angle in the cross-section passed normally to the hull side through the ice contact point. When applying the (1) equation one should remember that of the two contact points (bow and stern) it is necessary to take the one where the ice force delivers the greatest resistance to wedging. Hull angles have to be taken for the same point.

4 TURN AREA ESTIMATIONS

Let us describe the captain's manoeuver under specified ice conditions through the number of ship path apexes. Path apexes are understood here as points were the ship changes her direction. The first apex coincides with the initial ship heading, the last apex N is the final position. The angle between initial and final bearings varies within 180°.

Following the suggestion made in (Sazonov, 1995), we can understand the optimum turn as a turning manoeuvre which satisfies the condition of least ship motions: $\min \sum_{i=1}^{N-1} S_i$ where S_i is the travel of the ship during an i-th phase of the manoeuvre. The general formula for total motions may be written as:

$$S = \sum_{i=1}^{N-1} S_i = 2\left[R_B\left(\sin\Psi_1/2 + \sin\Psi_3/2 + \ldots\right) + R_S\left(\sin\Psi_2/2 + \sin\Psi_4/2 + \ldots\right)\right] \tag{2}$$

where R_S is the turning circle radius when running astern, R_B is turning circle radius when running ahead. Formula (2) should be complemented with $\sum_{i=1}^{N-1} \Psi_i = \pi$ (3)

The least total travel condition is for S derivatives in terms of Ψ_i to be zero. When computing the derivatives, the last even-number change of heading is written with the help of (3) as $\Psi_k = \pi - (\Psi_1 + \Psi_2 + \Psi_3 + \ldots)$. Equations corresponding to the least condition are shown below:

$$\frac{\partial S}{\partial \Psi_1} = R_B \cos \frac{\Psi_1}{2} - R_S \sin \frac{\Psi_1 + \Psi_2 + \Psi_3 + ..}{2} = 0$$

$$\frac{\partial S}{\partial \Psi_2} = R_B \cos \frac{\Psi_2}{2} - R_S \sin \frac{\Psi_1 + \Psi_2 + \Psi_3 + ..}{2} = 0 \tag{4}$$

....

Evaluations of (4) indicate that all even and odd heading angle changes are equal to each other. Final formulae for heading variation angles are:

$$\Psi_2 = 2 \arccos \left[\frac{R_B}{R_S} \cos \frac{\Psi_1}{2} \right] \tag{5}$$

$$\frac{R_B}{R_S} \cos \frac{\Psi_1}{2} = \sin \frac{m \Psi_1 + 2l \arccos \left[\frac{R_B}{R_S} \cos \frac{\Psi_1}{2} \right]}{2} \tag{6}$$

Here: m is the number of ship runs ahead, $N=m+l$ is the number of runs astern, *[..]* means the integral part of a number. The (6) formula is irrational and in a general case can be solved only numerically. Solutions of (5) and (6) enable to plot the ship path from which one can find the size of the required water area.

5 SHIP TURN TIME HISTORY ANALYSIS

Based on results obtained in the previous Chapter, the T time required to turn the ship with the captain's manoeuvre may be formulated as:

$$T = (N - [N/2]) \frac{R_B \Psi_1}{V_1} + [N/2] \frac{R_S \Psi_2}{V_2} + (N-2) t_r \tag{7}$$

where t_r is the time spent for reversing the engines. The (7) formula is more convenient when written for the case of equal ahead and astern turning circle radii: $R_B = R_S$. In this case, as follows from (5) and (6), it is $\Psi_1 = \Psi_2 = \pi / N - 1$, and $V_1 = V_2$. Then formula (7) can be written as:

$$T = \frac{\pi R}{V} + ((N-2) t_r \tag{8}$$

Evaluations of this formula allow to conclude that the time required for turning the ship with the captain's manoeuvre can't be longer than making a turning circle under same ice conditions. Under specified ice conditions there is no optimum number of wedgings into lead edges. The duration of the captain's manoeuvre is a linear function of the number of wedgings. With a specified number of wedgings the turning time can be minimised only by reducing the interval necessary for reversing the engines. These conclusions qualitatively agree with sea trial data of "Kapitan Chechkin" and "Kapitan Plahin" icebreakers (Tronin at al,1980).

6 CONCLUSIONS

This paper describes a theoretical analysis of ship motion characteristics when turning in ice by the captain's manoeuvre. The performed analysis has allowed to formulate the condition necessary for executing this manoeuvre: wedging into the ice edge. This condition enables to investigate the captain's manoeuvre in ice model basins. In model basins it is possible to study ship wedging ability both ahead and astern. If the subject ship has this ability, she will be capable of performing captain's manoeuvres under similar conditions.

Another important conclusion drawn from this study is that all major parameters of the captain's manoeuvre are functions of the turning circle radius. From this it follows that improving ship circulation performance should lead to enhancing parameters of the captain's manoeuvre. Thus, in spite of the fact that the turning circle is a comparatively infrequent choice for manoeuvring in ice-covered waters, circulation characteristics should be investigated while designing a new ship as thoroughly as it is done for ice performance parameters.

The paper offers an algorithm for calculating the water area necessary for turning with the captain's manoeuvre. This method may be utilised when considering different options of ship service roles.

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ANNEX A: DERIVATION MANIPULATIONS FOR THE WEDGING ABILITY CONDITION

Let us consider a ship sailing in an lead with a width of B_c. At the initial instant of the time history the rudder is tilted to the maximum possible angle. This is achieved instantaneously. Due to rudder application the ship acquires a certain angular velocity ω and a certain drift angle β. Both these values are time-dependent, and their time variation patterns are set by integrals of ship free motion equations like the ones described, e.g. in (Sobolev, 1976). After a certain short interval ship sides will touch ice edges and start interacting with them. This will generate an ice force and a moment which will try to "bounce" the ship away from the edge.
Ship hull points of contact with ice edges can be found using the method described in (Nemzer at al, 1995) which basically means solving a set of nonlinear algebraic equations representing contact conditions for two flat curves (the waterline and the ice edge). Established contact points dictate the ship heading angle which corresponds to the instant when hull sides touch ice edges. Taking into account the relation between the ship heading χ and the angular velocity $\chi = \int_0^t \omega(t)dt$, and utilising the ship free motion integrals, it is possible to find the angular velocity of the ship at the instant of contact with the ice edge ω_0.
Further motions of the ship interacting with ice edges are described by a differential equation as:

$$J_S \frac{d\omega}{dt} = F_R l_R - 2F_I l_I \tag{A.1}$$

where: J_S is the inertia moment found taking into account the added water mass; F_R, l_R is the rudder force and its arm;. F_I, l_I is horizontal component of ice force and arm. The factor of *2* indicates that we take into account two ice forces applied to the ship (at the bow and at the stern). This is done assuming that these forces are equal. In real life bow and stern lines are different, and therefore the respective forces are also different. Since the aim of the exercise is to get a top-side estimation of the rudder force required to wedge into the ice, in the (A.1) formula we should chose the ice force which produces the greatest resistance to wedging. The horizontal component of the ice force may be computed with:

$$F_I = \sigma_C S \cos \beta' \tag{A.2}$$

where: σ_c is the ice crushing strength; $S=2R^{0.5}V_n^{1.5}t^{1.5}$ is the crushing area; R is the hull side curve radius at the contact point; V_n is the wedging velocity normal to the hull side; t is time; β' is the hull slope angle at the subject cross-section passed normally to the ship side throgh the contact point. Then the (A.1) equation can be re-written as:

$$\omega = \frac{F_R l_R t}{J_S} - \frac{0.8\sigma_C R^{0.5} V_N^{1.5} l_I t^{2.5}}{J_S} + \omega_0 \qquad \text{(A.3)}$$

The hull will continue wedging into the ice till a certain instant t_B when the foremost ice segments would break off:

$$t_B = \frac{0.64\sigma_f^{0.67} h^{1.33}}{\sigma_C^{0.67} R^{0.33} V_N} \qquad \text{(A.4)}$$

where: σ_f is the ice bending strength; h is the ice thickness. Substituting (A.4) into (A.3) and taking into account the obvious inequality $\omega > 0$ which ensures that the ship does not bounce off the ice edge, we shall arrive to:

$$F_R > \frac{0.8\sigma_C R^{0.5} V_N^{1.5} l_I t_B^{1.5}}{l_R} - \frac{J_S \omega_0}{l_R t_B} \qquad \text{(A.5)}$$

The (A.5) formula can be simplified if we consider that the width of the channel broken by a ship in level ice would never be much greater than the beam of the ship. It means that there will be only a short interval till ship sides come in contact with the ice, and therefore no chance of generating any sizable angular velocity ω_0. Thus, the final formula for the wedging ability criterion may be written as:

$$F_R > 0.39 ctg\beta' \sigma_f h^2 \frac{l_I}{l_R} \qquad \text{(A.6)}$$