Large ship motion mechanics in “narrow” ice channel

A A Dobrodeev, N Yu Klementyeva and K E Sazonov
Krylov State Research Centre, St.Petersburg, Russia

E-mail: A_Dobrodeev@ksrc.ru

Abstract. The paper considers the motion mechanics of a large-size ship sailing in a “narrow” channel behind an icebreaker whose breadth is not as wide as that of the ship. Conditions when the ship is heading asymmetrically with respect to the channel axis are analyzed; ship ice resistance is estimated for the symmetric as well as asymmetric in-channel motion scenarios.

1. Introduction
The motion mechanics of large-size ships in ice conditions have practical importance in development of marine transportation systems to export hydrocarbons from the Russian Arctic regions. Recently, heavy-tonnage vessels have been increasingly used for cargo carrying purposes in the Arctic seas. The latest example is newly commissioned LNG carriers of “Christophe de Margerie” type. The advent of such vessels poses a range of challenges in the field of marine ice engineering, with the need to update the ice sailing tactics for the vessels of that size considered as one of the most important tasks [1].

The problem why traditional methods of ice sailing tactics are no longer fit for large-size vessels is that their hulls are much wider than the breadth of any icebreaker in operation or under construction. At present two methods of icebreaker-assisted operation are practiced in Arctic shipping, namely, a traditional approach when vessels are led by an icebreaker and an alternative option when two icebreakers are used [2].

A large-size carrier led by one icebreaker has to shoulder through a “narrow-width” channel grinding ice edges with her own hull. This scenario has been repeatedly examined in theoretical studies on Arctic shipping [3, 4]. Usually it is assumed that the ship’s centerline is aligned with the channel axis, while interactions of ship sides with the ice cover is symmetrical. However, sea trials as well as self-propelled model tests suggest that in some cases there is no such symmetric pattern for a large size vessel running in ice channel. In figure 1 there is a photo (borrowed from [5]) showing the Propontis oil tanker (beam 44 meters) led by the Taimyr nuclear icebreaker (beam 28 meters). It is well seen that the tanker is positioned in the channel to break ice cover with one side, her other side rubbing the ice edge. The purpose of our study is to consider the motion mechanics of a large ship sailing in a “narrow” ice channel.
2. Object and methods of investigation

Calculations of the ship motion were performed to find out the factors that influence the position of a large-size ship in a narrow-width channel as well as to determine ship’s ice resistance.

Two hypothetical large-size vessels of ice class were taken for the study. They are assumed to have the same main particulars, except the flare angle of parallel middle body. The first ship has no flare angle, while the second one has a flare of 10°. The principal dimensions are given in the table 1 below:

| Main data of large-size vessels |   |
|-------------------------------|---|
| Length on waterline, m        | 240 |
| Beam on waterline, m          | 50  |
| Draft, m                      | 12  |
| Middle body length, m         | 140 |
| Waterline slope at the bow, deg. | 45  |
| Angle of 0 frame, deg.        | 70  |

Forces induced by interaction with ice channel edges on ship hull were calculated in function of hull’s lateral offset from the channel axis. Also, net ice resistance of ship and total lateral ice force were estimated. The ice resistance was found using a semi-empirical formula of B.P. Ionov [6] providing quite a straightforward procedure to take into account the narrow ice channel as well as asymmetric pattern of ice breaking by ship sides. Under symmetric ship motion with respect to the ice channel axis a new hull is “constructed” with its breadth reduced by the channel width. The stem angle with respect to the running waterline is defined by the actual waterline angle at the point of contact with the channel edge, while the functions depending on the angles of ship’s frames are calculated for the hull length from the contact point of hull side/ice edge to the point of maximum hull beam. Appropriate corrections are introduced into the forebody length. At the asymmetric ship orientation with respect to the channel axis the above-described procedure is used to estimate the resistance of each hull side separately and the result should be reduced by half.

The method suggested by B.P. Ionov can be used only for estimating the ship ice resistance. Lateral forces on the opposite ship sides were found by applying one of the Shimansky coefficients $\eta_2$ expressed as follows [7]:

$$\eta_2 = \frac{\sum_{l}^{I}}{\sum_{ill}}; \quad \sum_{l} = \int_{0}^{L} \frac{\cos x' \cos y'}{\cos \alpha'}; \quad \sum_{ill} = k \int_{0}^{L} \frac{\cos^2 x'}{\cos \alpha'} dx;$$  \hspace{1cm} (1)
where \( \sum I, \sum III \) are total lateral and longitudinal forces on one ship side, \( \cos x', \cos y' \) are cosines of angles between the normal to the waterline point under consideration and the \( O_x \) -axis and \( O_y \) -axis \((x\)-axis is positive from midship to bow, \( y\)-axis is positive to starboard); \( \cos \alpha' \) is the waterline slope angle with respect to the point under consideration; \( L' \) - entrance length; \( k \) - proportionality factor.

This procedure was used to estimate ice-induced forces on the above-described hypothetical hulls of large-capacity vessels sailing straight with examination of variable offsets between ship’s centerline and the ice channel axis, starting from the symmetric case. The results are presented as plots of the total lateral force in figures 2 and 3. In these graphs the ice resistance of asymmetric cases is referred to the ice resistance found for the same vessel in the symmetric position.

**Figure 2.** Relative total lateral force versus ship CL offset from channel axis, channel width and ice thickness. Flare angle in way of parallel middle body is 0\(^\circ\). a – full curve; b – initial curve section at small offsets.

**Figure 3.** Relative total lateral force versus ship CL offset from channel axis, channel width and ice thickness. Flare angle in way of parallel middle body is 10\(^\circ\).
Ship ice resistance for asymmetric case was calculated as:

\[ R_f = \frac{R_{ad}}{2} (1 + f_d \eta_{m2}), \]  

where \( R_{ad} \) - ice resistance of the ship side breaking the channel ice edge; \( f_d \) - hull/ice friction coefficient; \( \eta_{m2} \) - Shimansky coefficient determined for the hull side part breaking the ice edge. Figure 4 presents the results as plots of the relative ice resistance versus the width of “narrow” ice channel.

3. Discussion

The data presented in figure 2 suggest the following mechanism causing a large-size vessel to deviate from symmetric motion in narrow ice channels. Firstly, as it is seen from figure 2b, the symmetric motion is stable at small excursions of the ship centerline from the channel axis. At small offsets a lateral restoring force is generated, returning the ship to her initial position with respect to the channel axis. However, stronger disturbances due to local ice thickness and/or strength variations may disrupt this equilibrium. Then the ship is exposed to a disturbing force (figure 2a) growing with the offset, and the ship position becomes unstable. Transition to another kind of stable state occurs, i.e. to an asymmetric ship position with respect to the channel axis, where the total lateral (restoring) force is zero. The asymmetric ship position is stable and it takes rather large forces to alter this ship orientation.

The above-described mechanism of loss in position stability may arise only if the ice resistance of starboard side, which is cutting into ice, happens to be less than that of the port side, withdrawing from ice. This situation is quite likely in case of large-size vessels, featuring vertical sides in way of the parallel middle body. At given ship dimensions her ice resistance depends on the bow shape [8] defined by angles of the waterline slope, angles of frames and bow lines. Most of the large-size vessels feature very small angles of waterline slope and frames in way of the entrance/middle body transition. If these parts of the hull come into contact with ice, the ice resistance is increased. If the ice contact area is shifted forward to the stem, the icebreaking performance is noticeably improved. For this reason it can be expected that there is a hullform solution for the large-size vessels enabling them to avoid or mitigate the above-discussed effect.
This assumption is confirmed by estimations for a large-size vessel whose frames in way of the middle body are inclined to 10°. The results illustrated in figure 3 show that at small excursions, when the angle of frames in way of the middle body have no practical effect on ice resistance, the ship position proves to be stable. At larger excursions the position stability depends of the “narrow” channel width. If the channel width is relatively small (30 m in our case study), then the symmetrical position of ship with respect to the channel axis is always unstable. It can be explained by the fact that in this case ice edges interact with those parts of the ship sides that tend to break ice by bending due to their geometrical characteristics. For this reason the ship side cutting into ice has larger resistance as compared to the ship side withdrawing from ice, which gives rise to a restoring lateral force.

In a wider ice channel its edges interact with those parts of ship sides whose geometric characteristics are not as good for this job, therefore the symmetry of position can be disrupted. It should be noted that in this case the disturbing force is much weaker than in the case when there is zero angle of side inclination in way of the parallel middle body.

Greater disturbing forces in case of vertical sides with zero flare in way of the parallel middle body are determined by a change of ice breaking pattern from bending to splitting and crushing. At 10° angle of hull side inclination there may be a situation when the ship would break ice in a relatively wide channel by bending combined with splitting and crushing patterns. It is for this reason that the level of ice forces is found to be significantly lower.

Fig.4 gives an idea of how the ice resistance of ship changes when the symmetry of motion with respect to the channel axis is disrupted. It is seen that a large vessel oriented asymmetrically in an ice channel has a noticeably lower ice resistance as compared to the symmetric scenario. In thick ice this reduction may reach 50%. However, when ship sides are inclined this resistance reduction is much less reaching up to 25%. This effect is explained by particulars of the ship hullforms. Anyway, the identified changes in ice resistance can be used for increasing the speed of vessels sailing behind icebreakers.

4. Conclusions
The loss of motion symmetry is described for large-size vessels sailing in ice channels behind an icebreaker whose hull breadth is not as wide as that of the vessels. Simple calculation formulas was used to qualitatively explain the mechanism behind this loss of symmetry related to specific hullform features of large-size vessels. It is found that when a large-size vessel is sailing through a “narrow” ice channel there can be one or two stable positions for the vessel. The symmetric position of vessel with respect to the channel axis is stable, but for vessels with vertical sides in way of parallel middle body this stability can be easily disrupted. In this case the vessel would take a stable asymmetric position, with one of her sides breaking ice, while the other side rubbing the channel edge. For vessels with inclined sides in way of parallel middle body the symmetric position could be always stable or the above-described asymmetric scenario could happen.

According to the calculations performed in this study the ice resistance of a large vessel sailing in ice thicker than 1 m is reduced under asymmetric orientation. Depending on the hullform this reduction may reach up to 50% of the ice resistance under asymmetric orientation. This fact should be taken into account in assigning the safe distances for large-size vessels led by icebreakers.

References
[1] Pustoshnyi A V, Sazonov K E 2015 Problems of shipbuilding science at the current stage of Arctic exploration Herald of the Russian Academy of Science 85(4) 316-20
[2] Sazonov K E, Dobrodeev A A 2014 Different technologies for making a wider channel in ice for large-size ships Proceedings of the International Offshore and Polar Engineering Conference ISOPE (Busan) pp 1171-6
[3] Sazonov K E 2011 Navigation challenges for large-size ships in ice conditions *Ship and Offshore Structures* **6** 231-8

[4] Dobrodeev A A, Sazonov K E 2018 Fast sailing in ice – the new goal of model studies *The Naval Architect* pp 22-4

[5] Ruksha V V, Belkin M S, Smirnov A A and Arutyunyan V G 2015 Structure and dynamics of cargo shipments via Northern Sea Route: history, present day and future prospects *Arktika: ekologia i ekonomica* **4**(20) 104-10

[6] Ionov B P, Gramuzov E M 2001 *Ship propulsion performance in ice* (St.Petersburg: Sudostroenie) p 512

[7] Kashtelyan V I, Ryvlin A Ya, Fadeev O V, Yagodkin B Ya 1972 *Icebreakers* (Leningrad: Sudostroenie) p 286

[8] Sazonov K E 2010 *Theoretical principles of ship sailing in ice* (St.Petersburg: Krylov Shipbuilding Research Institute) p 274