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# Ice interaction of carrier ships in drifting ice and under ice compression: theoretical description

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## ABSTRACT

Dynamic progress in Arctic shipping enables all-year-round transportation of oil & gas from offshore fields and growth of transit traffic along Northern Sea Route lanes, which paves way to development of new procedures for ship propulsion performance tests and, accordingly, theoretical models describing various ice navigation scenarios. As of today, scientific background in these areas is well behind the technical progress in development of large Arctic carrier ships. Recent designs and new buildings of Arctic carrier ships and icebreakers are unprecedented in terms of both size and power, and scientific support level of their development is high enough. Still, the operation of these ships poses the questions that were not investigated at the design stage. One of these questions is navigation in drifting ice.

Drifting ice fields and ice compressions may occur to the carrier ships in both offshore areas of the Arctic Ocean and the rivers of Siberia. Also, major Siberian rivers, like the Ob’ or the Lena, feature fast-ice fields, intense ship traffic breaks these fields into separate ice pieces further sent adrift by various natural factors. Considering that fairway width is always limited and the schedule of ship traffic must be strictly followed to ensure efficient operation of marine transportation system, the studies of ship propulsion performance in drifting-ice and ice compression conditions are extremely relevant.

Based on model test data, this paper discusses theoretical findings in the field of drifting-ice navigation of large ships, giving valuable insights into the character of forces acting on the hull moving asymmetrically in drifting ice and giving recommendations on how ice loads on hull could be reduced if a ship moves with a certain drift angle created by her steering and propulsion system operation. The paper also addresses the mechanism of hull-ice interaction in case of ice compression.

KEY WORDS: Ice drift; heavy-tonnage vessel; ice channel; ice resistance; friction force.

## INTRODUCTION

Arctic lanes are the shortest way of communication between major ports of Europe and Asia-Pacific. The Northern Sea Route, however, became available for large-size carrier ships only in recent years, due to the progress in icebreaker building and introduction of new marine propulsion systems offering much higher propulsive power for modern icebreakers, tankers and LNGCs. Still, even now large-size carrier ships mostly operate under icebreaker pilotage. Their autonomous navigation usually takes place in summer-autumn navigation period, when ice concentration, as well as its physical and mechanical properties, are below their peak values. Some modern ships, like those of Yamalmax class, already can navigate in winter-spring period, when ice conditions are considerably harder. Cargo deliveries, however, have to meet stringent deadlines, so even Yamalmax-class ships must use ice channels to deliver their cargo on time. One of the most common navigation challenges in ice channels is ice compression (Leisti et al., 2009)

The term compression in an ice cover refers to a situation where wind and/or current exert drag force on ice cover and the ice starts to drift. When wind drag acts on open pack ice, the ice floes start to move. If the ice motion is restricted by an obstacle like a shoreline, the ice cover starts to compact. First all the open water area closes. This is followed by rafting of ice at the contact points between ice floes. According to the one of approaches the ice compression is could be expressed as per a three-point scale, where 1 corresponds to weak compression and 3 corresponds to strong compression. Generally, ice compression is a particular case of ice drift, when an ice sheet moves due to an external force. In a vast majority of cases, ice drift speed is within 0.1 – 0.3 m/s, and its maximum value might be as high as 1.0 – 1.5 m/s (Sazonov 2019). Ship speed in ice is much higher than the speed of ice drift. Based on that, it may be concluded that ice drift plays only a minor role in ship navigation conditions. But when a ship has to move in hazardous environments, the effect of ice drift upon navigation conditions must always be considered. A good illustration for this is ship traffic in the Gulf of Ob', where the ice frequently drifts across a narrow fairway.

The scenarios of ship navigation in drifting-ice environments could be different:

- continuous level ice. If a ship moves in drifting ice field (or its fragments), ice interaction of its hull will be the same as in fast-ice conditions. Ice drift leads to a slight and rather slow change in heading that can be compensated by the operation of rudders or pod propulsion units. This scenario is of the least interest because large ice fields and their fragments usually drift at a low speed.
- pack ice and ice cakes. These conditions might sometimes feature the greatest drift speeds. Here, the ship might move both autonomously and under icebreaker pilotage. In the latter case, large ice-going ships move in a "narrow" channel and break the edges by their sides. It happens because large carrier ships are considerably wider than any of the existing icebreakers. For example, nuclear icebreaker LK-60, the most powerful in the world and commissioned in 2020, has its hull beam equal to only 34 m, whereas Yamalmax-class Arctic carrier ships (currently in service and under construction) have a breadth up to 50 m.

This paper describes a calculation method for ice loads on hull of the ship moving in ice at a certain drift angle. This method is universal: it depends neither on ice conditions nor on navigation scenario (autonomous / icebreaker pilotage). Numerical examples will be given for autonomous navigation in ice cakes and for icebreaker pilotage with "narrow" channel. The resistance of ice cakes will be determined as per the method suggested by A. Ryvlin and described in Kastelyan et al (1968). Similar calculations could be also performed for the navigation in continuous level ice and pack ice, in which case ice resistance calculations will require the mathematical models adequately representing these ice conditions. Ice resistance calculation procedure for pack-ice navigation conditions is given in Sazonov & Dobrodeev (2011).

## CALCULATION METHOD

Sazonov (2006) gives a calculation procedure for ice loads on a ship following a curvilinear trajectory in ice. This procedure is based on the distribution of ice load over the length of hull-ice contact areas. It may be adapted for the scenario when a ship moves at a certain drift angle. The assumptions adopted in this procedure are as follows:

– positional hydrodynamic forces and moment that always arise on hull when a ship moves with a certain drift angle are not considered because they are much lower than ice-induced forces, especially at small drift angles and low ship speeds to be discussed later in this paper. If necessary, these forces may be taken into account as per the procedure given in [12].

– as ship moves in ice at a certain drift angle, ice interaction of its sides is asymmetric because the lengths of their respective ice contact areas become different. These lengths are determined as per the assumption that hull-ice contact occurs when the projection of speed at given point of waterline onto the external normal line drawn towards the hull is above zero.

### *Determination of hull load distribution law: running at a certain drift angle in level ice*

Let us have a closer look at the approach to determination of hull-ice contact areas for a ship moving at a certain drift angle. The normals will be defined in ship-axes Cartesian coordinate system *OXY* with the origin at ship CG, axis *OX* positive forward and axis *OY* positive towards the port side. Normal velocity is specified for the outer side ($v_n^{ex}$) towards which velocity vector is directed, and for the inner side ($v_n^{in}$) accordingly as per the expressions below:

$$\begin{aligned} v_n^{ex} &= v_S \sin(\alpha + \beta) \\ v_n^{in} &= -v_S \sin(-\alpha + \beta) \end{aligned} \qquad (1)$$

where $v_s$ is the speed of ship CG, $\beta$ – drift angle, $\alpha = \alpha(x)$ – entrance angle at given hull point. This formula can be obtained from ship lines drawing in *OXY* coordinate system. To find X-coordinate for the end point of external ($x_1$ negative) and internal ($x_2$) zones of hull-ice contact, Expressions (1) must be adopted as equal to zero and solved numerically.

To find the law of ice load $q_I$ distribution over contact zone length, it is assumed that normal (with respect to the side) ice load per unit length at each point of waterline is a sum of two components (Kashtelyan et al, 1968):

– static, proportional to a certain effective half-breadth of hull at given point;

– dynamic, proportional to the normal speed with respect to side.

Let us write the equation including these two components:

$$q_I = k_S B_{ef} + k_d v_n \qquad (2)$$

where $k_s$ is static proportionality coefficient, $k_d$ – dynamic proportionality coefficient, $B_{ef}$ – effective half-breadth of hull at given point. Effective half-breadth is a parameter that characterizes apparent increase or decrease in half-breadth of inner/outer side with respect to ship movement direction.

It is evident that the greatest ice loads are applied to a certain part of the outer contact zone in the aft of the ship. Higher ice load on the outer side in the aft is also confirmed by the numerical calculations performed by Lindstrom (1990). The term of effective half-breadth in Formula (2) above takes this greater ice load into account.

***Determination of effective half-breadth and proportionality coefficients***

Effective half-breadth is defined as a perpendicular drawn from the given point of external or internal side onto the straight line passing via the stem and co-directional with the total speed vector at the said point. This effective half-breadth is calculated as:

$$B_{ef}^{ex} = \frac{|y|}{\cos\beta} + \left(\frac{L}{2} - x - y\tan\beta\right)\sin\beta,$$
$$B_{ef}^{in} = \frac{|y|}{\cos\beta} - \left(\frac{L}{2} - x + y\tan\beta\right)\sin\beta, \quad (3)$$

where $x$ and $y$ are the coordinates of given hull point in the ship-axes system. An example of $B_{ef}^{in}$ definition at some point on the inner side is shown in the figure 1.

To obtain proportionality coefficients, Formula (2) contains the data on ice resistance of ship in given conditions of ice navigation. Ice resistance itself, for a ship running straight ahead, is expressed as a linear function of ship speed, i.e. as $R_I = R_{IS} + Av_S$, where $R_{IS}$ is “direct” ice resistance. This assumption may be regarded as completely true when the ship moves in ice with the thickness exceeding a half of its limit ice-breaking capability. When this condition is not met, it is possible to use piecewise-linear approximation of ice resistance as function of ship speed. The third hypothesis enables determination of proportionality coefficients as per available data on ice resistance using the expressions below:

$$k_S = \frac{R_{IS}}{2\int_0^{L/2} y(x)(\cos\beta'\sin\alpha + f_{Id}\cos\varphi\cos\alpha)dx}$$
$$k_d = \frac{A}{2\int_0^{L/2} \sin\alpha(\cos\beta'\sin\alpha + f_{Id}\cos\varphi\cos\alpha)dx} \quad (4)$$

where $y(x)$ is the equation of ice waterline in CG-axes coordinate system, $f_{Id}$ – dynamic coefficient of hull plating friction against ice, $L$ – ship length, $\beta'$ – frame angle in the section normal to the side, $\varphi$ – buttock angle.

Expressions (2) and (4) are universal and can handle both calculation results and experimental data on ice resistance to calculate ice-induced loads and moment for a ship moving in ice with a certain drift angle. The same approach enables determination of ice-induced forces and moments for arbitrary movement of ship in broken ice, as well as for different navigation conditions pertinent to ice resistance, e.g. shallow water. Specifying ice resistance of ship, Expressions (4) automatically take into account physical and mechanical properties of ice, as well as its thickness.

***Determination of ice-induced forces and moments acting on the hull of ship moving in ice at certain drift angle***

Ice-induced forces and moment at given gyration speed $v_S$ and drift angle $\beta$ of the ship are calculated as per the expressions below:

$$X = \int_{x_1}^{L/2} \left(k_S B_{ef}^{ex} + k_d v_n^{ex}\right)\left(\cos\beta' \sin\alpha + f_{Id} \cos\varphi \cos\alpha\right) dx +$$

$$+ \int_{x_1}^{L/2} \left(k_S B_{ef}^{in} + k_d v_n^{in}\right)\left(\cos\beta' \sin\alpha + f_{Id} \cos\varphi \cos\alpha\right) dx$$

$$Y = \int_{x_1}^{L/2} (k_s B_{ef}^{ex} + k_d v_n^{ex})(\cos\beta' \cos\alpha - f_{Id} \cos\varphi \sin\alpha)\, dx -$$
$$\int_{x_2}^{L/2} (k_s B_{ef}^{in} + k_d v_n^{in})(\cos\beta' \cos\alpha - f_{Id} \cos\varphi \sin\alpha)\, dx$$

$$M = -\int_{x_1}^{L/2} (k_s B_{ef}^{ex} + k_d v_n^{ex})(\cos\beta' \cos\alpha - f_{Id} \cos\varphi \sin\alpha)\, x\, dx +$$
$$\int_{x_1}^{L/2} (k_s B_{ef}^{ex} + k_d v_n^{ex})(\cos\beta' \sin\alpha + f_{Id} \cos\varphi \cos\alpha)\, y\, dx + \qquad (5)$$
$$\int_{x_2}^{L/2} (k_s B_{ef}^{in} + k_d v_n^{in})(\cos\beta' \cos\alpha - f_{Id} \cos\varphi \sin\alpha)\, x\, dx -$$
$$\int_{x_2}^{L/2} (k_s B_{ef}^{in} + k_d v_n^{in})(\cos\beta' \sin\alpha + f_{Id} \cos\varphi \cos\alpha)\, y\, dx$$

Here, ice-induced moment is calculated taking into account that it is caused not only by the transverse force but also by the resistance force. Parameters $x_1$ and $x_2$ are the boundaries of hull-ice contact zones for outer and inner hull respectively, as yielded by Expressions (1).

***Adaptation of the calculation method for ice-channel navigation***

The expressions above are true for autonomous ice navigation. To handle the scenario of ice-channel navigation under icebreaker pilotage, these expressions require minor alterations. The method for ice resistance calculation taking ice channel into account has already been described in Dobrodeev et al. (2018), and its main points are as follows:

– The calculations require construction of the new waterline for the hull under investigation.

If the ship is positioned symmetrically with respect to channel axis:

- the “new” hull beam will be the “old” hull beam minus channel width.
- entrance angle of waterline will in this case be determined by the entrance angle of the real waterline at the point of its contact with channel edge;
- the functions dependent on frame station angles are calculated for the interval from the point of hull contact with channel edge to the point of the maximum beam;
- stern length is updated accordingly.
- once all these steps are complete, it becomes possible to calculate ice load on hull.

If the position of ship is not symmetric with respect to channel axis, i.e. if the ship moves at a certain drift angle:

- perform the steps above to calculate the resistance for each side separately. The results will have to be divided by 2, because calculation expressions were derived for two sides at once.

– During the calculation, the first step is to obtain ice resistance for the ship moving straight forward along the channel, and then to obtain the ice load taking drift angle into account. Ice-hull contact zones are determined for given ship orientation in the channel, see the red highlights in Figure 1 below. The same Figure also shows ice drift speed $V_d$, ship speed $V_s$ and drift angle $\beta$.

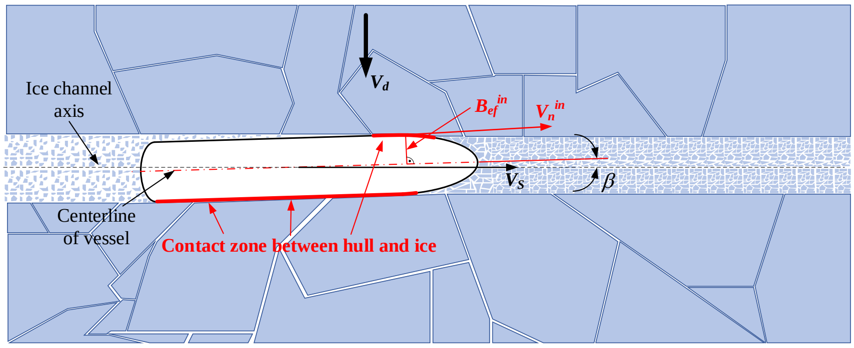



Figure 1 – A large carrier ship moving at drift angle $\beta$ along the channel with concentrated broken ice

## NAVIGATION WITH DRIFT ANGLE: FEASIBILITY CONDITIONS

Irrespectively to the scenario of navigation with drift angle (autonomous navigation or icebreaker pilotage), there is a number of conditions that have to be met. Moving with drift angle, the ship suffers external moment $M$, as well as longitudinal and transverse components in the main vector of external forces, i.e. resistance force $R$ and lateral force $Y$ respectively. All external forces and moment acting on the ship have hydrodynamic and ice-induced component. In general, feasibility conditions for movement with drift angle are as follows:

- for ships with conventional propulsion (rudders):

$$R = \sum_{i=1}^{N_1} T_{Ei}; \quad Y = \sum_{i=1}^{N} F_{Ri}; \quad M = \sum_{i=1}^{N} F_{Ri} l_i \,, \tag{6}$$

- for ships with pod propulsion:

$$R = \sum_{i=1}^{N} T_{Ei} \cos\delta_i; \quad Y = \sum_{i=1}^{N} T_{Ei} \sin\delta_i; \quad M = \sum_{i=1}^{N} T_{Ei} l_i \,, \tag{7}$$

where $T_{Ei}$ is the thrust of $i^{th}$ ship propulsor; $N_1$ – number of ship propulsors; $F_{Ri}$ – transverse force on $i^{th}$ rudder; $l_i$ – arm of the force arising on the control tool (with respect to ship CG); $N$ – number of ship control tools; $\delta_i$ – turning angle of ship control tool. Transverse force on the rudder is obtained from hydromechanical experiments and calculations performed as per well-known procedures (Makovsky, 1996).

These expressions mean that steady movement of ship with drift angle is only feasible if all external forces are compensated by ship steering and propulsion tools, which, in its turn, considerably depends on their composition and arrangement:

– the ship with one conventional rudder is practically unable to move steadily with constant drift angle because one rudder is not enough to simultaneously compensate lateral force and moment;

– the ship with two or more shafts can generate a slight torque enabling it to perform the maneuver under investigation. The torque is generated by the propellers operating in opposite directions;

The ship with pod propulsion can compensate external forces relatively easily. Its speed will be completely determined by the quantity and turning angles of pod units, as well as by ice conditions.

## CALCULATION RESULTS AND DISCUSSION

The calculation was performed for a large carrier ship with the following main parameters:

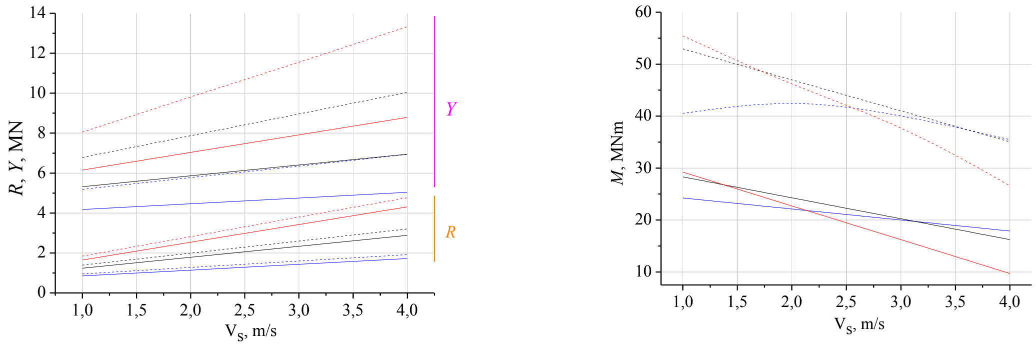
Table 1. Main parameters of large carrier (case study):

| Parameter | Value |
|---|---|
| Length O.A., m | 290.0 |
| Length B.P., m | 145.0 |
| Beam, m | 50.0 |
| Draught, m | 14.0 |
| Stem angle, deg. | 30.0 |
| Entrance angle at Frame Station 0, deg. | 70.0 |

### *Hull load calculation: autonomous navigation*

The mathematical model described above was used to calculate the load on the hull of a large carrier ship moving with drift angle.

Waterline shape and distribution of frame angles were adopted as per the recommendations of Sazonov (2006).




a b

Figure 2. Ice-induced forces (a) and moment (b) acting on a large ship moving with drift angle in broken ice.

*R* – resistance force, *Y* – transverse force, *M* – ice-induced moment; solid curves - drift angle $\beta = 2^0$; dashed curves – $\beta = 4^0$; blue colour – ice thickness 1 m; black – 1.5 m; red– 2 m.

The first stage of calculations was intended to obtain ship resistance in broken-ice conditions. The calculation was performed with and without consideration of the channel made by the icebreaker. Relative channel width $B_c/B_s$ varied from 0 to 0.8 with the step of 0.2. Ice resistance data were further used to determine unknown coefficients of the mathematical model as per Expressions (4). The next step was to calculate ice load on the hull of a large carrier ship moving with drift angle.

Calculation results for the autonomous-navigation scenario are given in Figure 2.

Analysis of the data in this Figure, highlights certain peculiarities of large ship movement with drift angle:

- Drift angle considerably increases ice loads on hull, whereas the increase in ice resistance is the smallest. The most important point is the growth of transverse force (at zero drift angle this force is zero, too). Transverse ice-induced force occurs due to the asymmetry of hull interaction with drifting ice. For large ships, this asymmetry is further aggravated by long parallel midbody: one of its sides interacts with ice over its whole length, whereas the other side has practically no ice interaction. This asymmetry also causes ice-induced moment determined with respect to ship CG. In terms of compliance with Criteria (6) and (7), transverse ice-induced force might be the hardest to compensate.
- For a ship moving autonomously, greater drift angle means greater ice loads on hull. As ice thickness grows, ice-induced forces grow, too. Ice-induced moment has a more complex relation with ice thickness because ice thickness determines the shape of ice pressure fluctuations on hull within contact areas. As ship speed grows, ice-induced forces tend to increase, which is also caused by the change in ice pressure distribution over hull.
- The calculations were performed only for two drift angles: $2^0$ and $4^0$. The reasons for choosing these angles were as follows:
  - Based on the condition that transverse ship speed must be the same as the speed of ice drift, it is possible to obtain the relationship of $V_d = V_s tg\beta$, where $V_d, V_s$ are ice drift speed and ship speed respectively. The calculation as per this formula performed for ship speeds of up to 4 m/s have shown that drift angles within $4^0$ correspond to ice drift speeds $V_d < 0.25$ m/s. These results for drift speeds have a good correlation with commonly observed pictures of ice drift.
  - Another reason for the limitation of drift angle range were calculation results shown I Figure 3 above: according to them, at $\beta > 4^0$ ice load on hull grows considerably, making the ship unable to move any further.

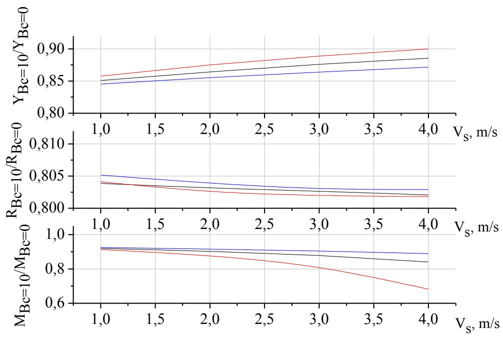
***Hull load calculation: channel navigation***

This part of the study was intended to determine the effect of ice channel upon ice-induced loads on the hull of a ship moving in it. The results of these calculations are given in Figure 4 below. For convenience of understanding, these results are shown in non-dimensional form to facilitate the estimation of ice channel effect upon ice-induced hull loads. Therefore, all calculation results for ice-channel conditions are given as percentages of their respective counterparts in the autonomous navigation scenario. During the calculation of ice-induced forces and moment as per Expressions (5), the integration was performed for hull-ice contact zones defined not only as per Expression (1) but also taking the ice channel into account, see Figure 3.

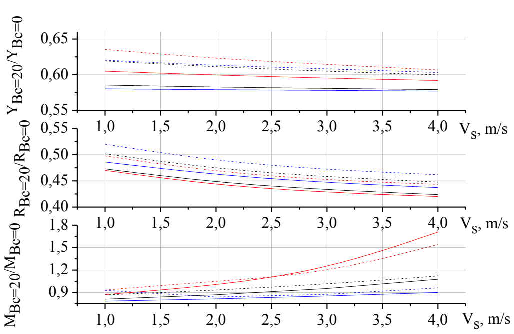
Let us investigate the contribution of various factors to ice-induced forces and moment:

- similarly to the autonomous navigation, greater ice thickness and drift angle result in greater ice resistance and transverse ice-induced force. These forces tend to decline considerably as relative channel width $B_c/B_s$ increases: at $B_c/B_s = 0.8$, ice resistance might become as low as 10% and transverse force as low as 20-25% of their autonomous-navigation levels.

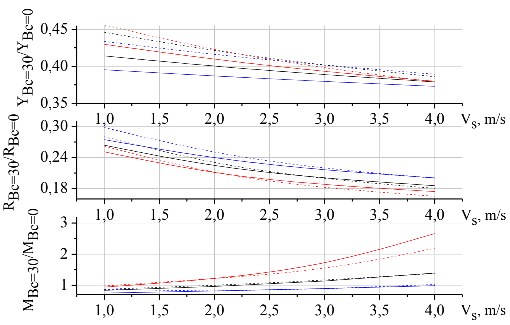
– ice-induced moment also considerably depends on relative channel width: at $B_c/B_s = 0.2$, similarly to autonomous-navigation conditions, ice-induced moment tends to decline as ship speed grows. At higher $B_c/B_s$, the picture becomes the opposite, i.e. ice-induced moment at higher speeds will increase in proportion with drifting ice thickness. The reason for this is the asymmetry of hull-ice interaction, further exacerbated by the ice channel because when a large carrier ship moves in the channel, its bow does not interact with broken ice. In autonomous-navigation condition, ice interaction of the bow was creating the ice-induced moment that contributed to maintaining necessary drift angle, thus relieving the torque required from ship controls.



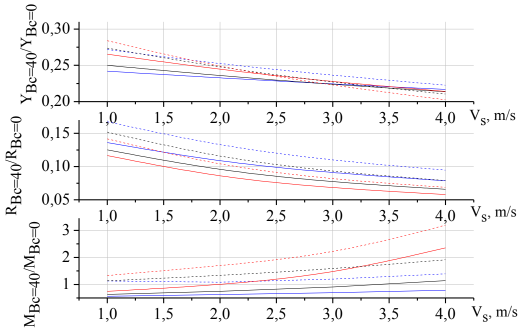

*a*




*b*




*c*




d

Figure 3 – Ice-induced forces and moment acting on a large carrier ship following the icebreaker in broken-ice channel with a certain drift angle.

$$a - \; B_c/B_s = 0.2; \; b - \; B_c/B_s = 0.4; \; c - \; B_c/B_s = 0.6; \;\; d - \; B_c/B_s = 0.8$$

Therefore, it may be concluded that when a large carrier ship moves in a drifting-ice channel with a certain drift angle, one of the primary tasks for the shipmaster is to compensate the growth of ice-induced moment. The estimates of this parameter lead to the conclusion that considerable length of large carrier ships makes the compensation of ice-induced moment feasible.

## CONCLUSION

This study was a theoretical analysis intended to estimate the feasibility of large carrier ship movement in drifting ice at constant heading angle. The analysis has shown that this movement is feasible but has to be performed with a certain drift angle to compensate the side shift due to drifting ice. Feasibility of this movement becomes especially important when a ship goes through an area with navigation hazards, e.g. follows a narrow fairway in shallow waters.

Theoretical analysis has shown that a ship moving with drift angle suffers a quite considerable redistribution of ice pressure on its hull due to the asymmetry of ice contact zone. This asymmetry increases ice resistance and creates transverse ice-induced force and moment that have to be compensated by ship controls. In autonomous navigation conditions, the feasibility of movement with drift angle is limited by design peculiarities of steering and propulsion system and thrust performance of given ship. These limitation might result in an emergency when a ship moves in the area with navigation hazards.

One of possible ways to mitigate the probability of hazardous situations is icebreaker pilotage. Theoretical analysis has shown that if the channel made by the icebreaker is wide enough, ice loads on the hull of carrier ship might decline considerably. Still, the ships moving in ice channel with drift angle have to face the growth in ice-induced moment, but for large ships this growth is not a critical issue. Therefore, icebreaker pilotage is the best option when a large carrier ship has to go through an area with navigation hazards.

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