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THE INFLUENCE OF THE ORIENTATION OF LEADS RELATIVE TO THE GENERAL COURSE OF AN ICEBREAKER UPON THE SPEED AND EFFICIENCY OF ICE NAVIGATION

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ABSTRACT

The experience of North Sea Route shipping hydrometeorological support has shown that one of the most important ice parameter effecting the winter navigation efficiency is the type of orientation of discontinuities in the ice cover (leads, cracks, canals) relative to the course of icebreaker. Five main types were identified.

The probability estimates of ice shipping distances, the regularities of distribution and variability of the main ice cover parameters and exploitation indicators of ship motion are obtained for every type of ice zone. The algorithm taking into account the leads characteristics when calculating the speed and time expenditures of icebreaker motion (including motion by ramming) and some other exploitation indicators is suggested.

INTRODUCTION

As a rule, in winter-spring period, when the ice cover of freezing seas reaches its maximum, the optimal routes of navigation go along the flaw polynyas or discontinuities through the ice massifs. Let us note that discontinuities include fractures, cracks and leads in the ice cover.

Practice of hydrometeorological information support of high-latitudinal voyages and transit cruises along the Northern Sea Route allowed Makarov and Frolov to determine that the type of orientation of discontinuities in the ice cover relative to the general course of an icebreaker is one of the most important characteristics of navigation conditions (Frolov and Brovin, 1995; Frolov, 1997).

Five main types were identified (Frolov, 1995):

- **Type A** - zone of "oriented" discontinuities: prevailing orientation of the system of discontinuities and the general course of icebreaker coincide or differ not more than by 30°;
- **Type B** - zone of "non-oriented" discontinuities: the orientation degree of discontinuities is small or the prevailing orientation of discontinuities differs from the general course of icebreaker more than by 30°;
- **Type C** - zone of increased fracturing of the ice cover: navigation is, as a rule, in the oriented zone with prevailing broken forms of the ice cover;
- **Type D** - zone of the absence of discontinuities: icebreaker motion is in compact ice (concentration of 10 tenths) with prevailing big ice floes;
- **Type E** - zone of decreased concentration of the ice cover: pronounced discontinuities are absent, icebreaker moves in the ice which is equally distributed over the area, its concentration is 8 tenths and less. The zones of such type are characteristic for the summer period and for the marginal regions in spring period.

In April-May, 1998, escorting of «Uikku» tanker from Murmansk to the Ob Bay and back was executed successfully within the frames of ARCDEV Project (Arctic Demonstration and Exploratory Voyage). The utilisation of flaw polynyas and discontinuities in the ice cover provided high velocities of escorting and completing the voyage by the terms planned in advance.

During the ARCDEV expedition within the frames of Work Package 3 (Ice conditions) and Work Package 5 (Ice routing) the visual ice observations were being carried out from board of «Kapitan Dranitsyn» icebreaker which was a member of convoy. Observations included determination of the ice cover characteristics directly on the route of the icebreaker in the area whose width was 6 times as wide and the length was 3 times as long as the width and the length of the icebreaker hull, respectively. The observed parameters included concentration and age categories, thickness, concentration of hummocks and ridges, stages of melting, prevailing ice forms, presence and intensity of ice pressures. Particular attention during ice observations was given to determination of the type of orientation of discontinuities in the ice cover relative to the general course of icebreaker. Along with ice observations some operating characteristics were recorded: mean speed in the uniform ice zone, transit time, characteristics of motion by ramming and power developed by the icebreaker's power plant. Based on the special ice observations, the database on all ice cover characteristics on the navigation route during the voyage was set up.

DISCUSSION

The most significant effect from discontinuity usage is usually reached when sailing through the ice massifs mainly consisting of thick first-year thick and first-year ice of medium thickness. During the ARCDEV expedition the sailing through such ice took place on two segments: from Zhelaniya Cape to the point 77°02' N, 77°08' E, and from the point 73°55' N, 71°22' E to the Kara Gate. The ice cover on these segments mainly consisted of first-year thick and medium ice, the share of young and new ice did not exceed 15 %, total ice concentration according to satellite images was equal 100 %. Further we will use the observation results obtained just on these segments.

According to the special observation results, the major part of these two segments was located in the type A and B zones (Table 1), i.e. the navigation was conducted with maximum possible usage of discontinuities. Not significant length of the type C zones is typical for the winter and spring period, when large ice floes and vast ice breccia prevail in the Arctic seas. The typical spatial scales of homogeneous ice zones and the type of discontinuity orientation practically coincide (Table 1), however the zones without discontinuities (type D) are characterized by the largest variability of length.

Table 1. Relative total length of the route and the characteristic scale of the uniform ice zones with the different type of orientation of discontinuities

Parameter	Zone type			
	A	B	C	D
Relative length, %	35	33	4	28
Characteristic scale, miles	3.28	3.27	2.22	3.17
Standard deviation, miles	4.49	2.74	4.21	4.74

The discontinuity width distribution for every type of zone has significant variability. (Figure 1). In the zones where the discontinuities are directed mainly along the general course of icebreaker (type A), the frequency of occurrence of discontinuities wider than the ship (icebreaker) - about 25 m - is equal to 90 %. In the zones of type B and C the frequency of occurrence of such discontinuities is equal to 47 % and 23 % respectively.

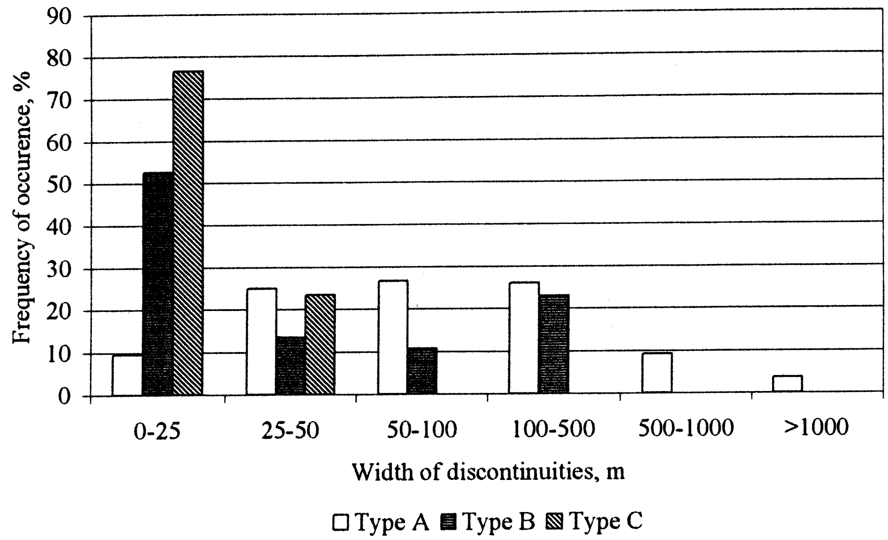

Figure 1. The discontinuity width distribution in the zones with different type of orientation.

The exploitation speed of icebreaker is the integral parameter of interaction within the system «ice - ship». It indicates the efficiency of using the ship of a certain class (Gordiyenko et al., 1967). The distribution of route length by the speed ranges gives an opportunity to determine the zones of the most effective navigation (Figure 2).

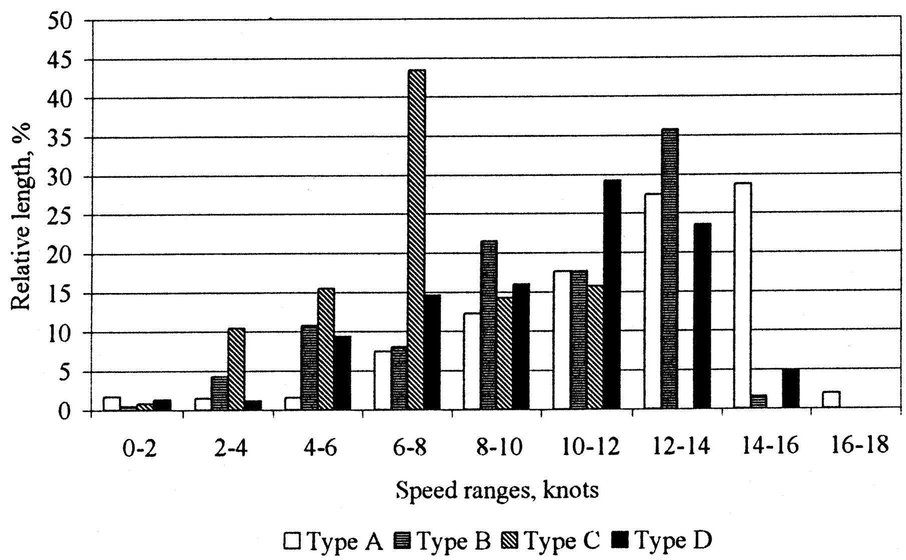

Figure 2. Distribution of the relative route length by speed ranges in the zones with different orientations of discontinuities

The analysis of speed distribution depicted on Figure 2 shows that the most favourable zones for navigation are the zones with discontinuity orientation of type A, the least favourable ones are the zones with high fracturing of ice cover (type C). Such unfavourable navigation conditions in the type C zones in the winter-spring period are caused by the fact that these zones are as a rule located in the regions of large horizontal gradients of ice drift velocity; these regions are usually characterised by greater amount of hummocks and high frequency of compressing. The characteristics of speed distribution in the zones of unfavourable discontinuity orientation (type B) and in the zones without discontinuities (type D) are close to each other (Table 2). Thus, the presence of discontinuities with orientation not coinciding with general course of the ship practically does not have an influence upon the speed.

Table 2. The characteristics of navigation speed distribution in the zones with different type of discontinuity orientation.

Parameter	Zone type			
	A	B	C	D
Average speed, knots	11,8	10,1	7,0	10,0
Length of the route with speed more than 10 knots, %	76	55	16	58
Length of the route with speed less than 6 knots, %	5	15	27	12

These conclusions may be confirmed by the data of navigation by ramming. In the type A zone the relative length of the route where the ramming was used was equal to 2 %, while in the type C zone - 38 %. In the type B and D zones the icebreaker moved by ramming at 7% and 5 % of the route respectively. It should be noted that the data of ramming concern to «Kapitan Dranitsyn» icebreaker. As for the same information regarding «Rossiya» icebreaker, it is, unfortunately, not available for the authors.

A very important indicator allowing us to estimate the discontinuity usage effectiveness is a criterion suggested by G.Lilljeström (Lilljeström, 1994). This criterion named «lead index» is defined as a time spent for sailing in young ice and open water. The lead index is estimated when both sides of the ship are not in contact with ice thicker than 20 cm. The lead index was calculated as the ratio of time of sailing through young ice or open water to the total time of sailing through the homogeneous ice zone. The observation executed during the ARCDEV expedition allowed determining the lead index for the zones with different discontinuity orientation.

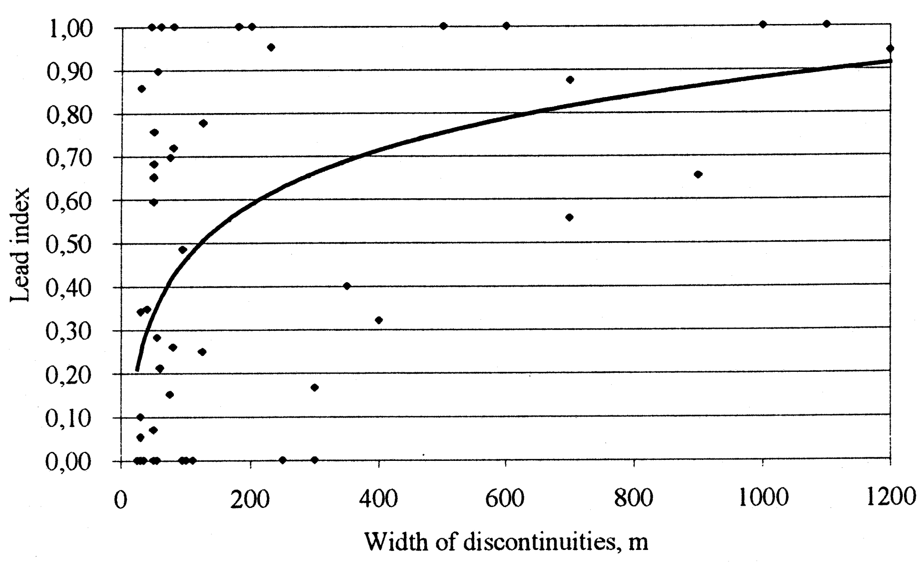

Figure 3. Lead index versus discontinuity width in the type A zones.

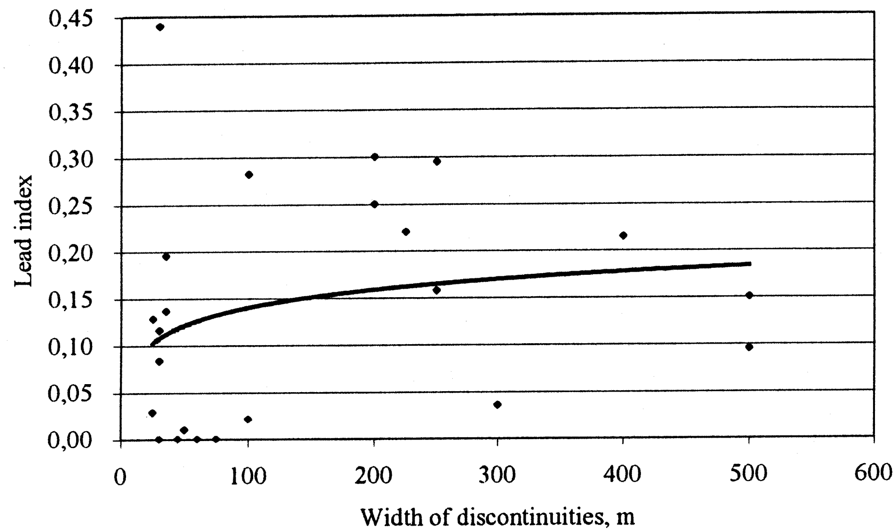

Figure 4. Lead index versus discontinuity width in the type B zones.

The mean value of the lead index for the type A zones appeared to be equal to 0.43, for the type B zones - 0.05, for the type C zones - 0. It is obvious that the lead index depends on the width and length of discontinuities. This dependence can be approximated by the logarithmic function (Figure 3,4)

for type A zones:

$$Li = 0.1817\ln(W) - 0.375 \tag{1}$$

for type B zones:

$$Li = 0.0272\ln(W) + 0.0149 \tag{2}$$

where L_i is the lead index, W is the width of the discontinuity.

It is worth noting that the approximation is executed for the discontinuities not less than 25 m wide (i.e. more than icebreaker width), because for narrower discontinuities the lead index is equal to 0.

The noted peculiarities of navigation using the discontinuities of ice cover can be and should always be taken into account when planning an ice voyage.

It is well known that before executing any marine operation in the ice covered sea, the ice cover parameters should be studied along with the other preparation measures. It can be done with the help of satellite images which give the information of total ice concentration, stages of development (that is equivalent of the approximate ice thickness estimate), prevailing ice floe sizes, amount of ridges, stage of melting as well as presence and orientation of the discontinuities. Principally it is enough for estimating the expected speed of an icebreaker of certain type or a standard convoy. For this purpose the model of quantitative assessment of ice navigation difficulty known as QAD model may be applied (Fedyakov & Brovin, 1995). This model allows taking into account the existence of discontinuities by means of special additional coefficient that depends on the type of icebreaker or convoy. At the same time, as it was shown above, not only the presence of discontinuities but also their predominant orientation should be taken into account. Otherwise the estimation of the speed can contain significant errors.

This problem may be solved in a following way.

Using the known actual distribution of the ice cover parameters the zones with different types of orientation of discontinuities are revealed. Then, using formula (1) and (2), the lead index for every zone is determined.

With the help of the QAD model the speed V_D in the zone without discontinuities (type D), the speed V_C in the zone with highly fractured ice cover (type C) and the speed V_L just in the discontinuity (open water or young ice) are estimated.

The estimate of the speed in the zones with clear discontinuity orientation (type A and B) is executed using the lead index of each zone. As in the type A and type B zones the ship moves partly through unbroken ice cover that is equivalent to type D, and partly just along the discontinuity, the speeds V_A and V_B in the type A and B zones respectively are determined as weighted mean values:

$$V_A = V_D(1 - L_{iA}) + V_L L_{iA} \tag{3}$$

$$V_B = V_D(1 - L_{iB}) + V_L L_{iB} \tag{4}$$

Thus the total time expenditures consist of partial expenditures spent for sailing through every zone:

$$T_{total} = \frac{S_A}{V_A} + \frac{S_B}{V_B} + \frac{S_C}{V_C} + \frac{S_D}{V_D} \tag{5}$$

This approach was applied for the ARCDEV voyage (Table 3). The average speeds of convoy calculated for every type of discontinuity distribution using stated algorithm correlate with actual values better than those calculated by means the of QAD model without taking into account the discontinuity orientation.

Table 3. Calculated and actual speeds of ARCDEV expedition convoy in the zones with different orientation of discontinuities.

Zone type	Lead index	Speed calculated without taking into account the discontinuity orientation, knots	Speed calculated taking into account the discontinuity orientation, Knots	Actual speed, knots
A	0.43	11.5	11.6	11.8
B	0.05	11.5	10.1	10.1
C	0	6.8	6.8	7.0
D	0	9.9	9.9	10.0

CONCLUSIONS

The observation data obtained during the ARCDEV expedition confirmed the hypothesis regarding the necessity to take into account the discontinuity orientation for estimating the ice navigation speed. The elaborated algorithm based on the usage of the lead index allows executing this estimate more precisely. However, the most serious difficulty is to estimate the lead index in advance. The matter is that the scale of the discontinuities visible on a satellite image is restricted by the resolution of this image. Often a large discontinuity distinguishable on the image in fact consists of a system of smaller discontinuities located closely to one another. If high resolution information is available, it is possible to estimate the statistical parameters of smaller discontinuities and then to determine the lead index for every zone of the voyage rather reliably directly from the image.

But if the information of only medium or low resolution is available, the following problem rises: how to find the correlation between the parameters of a large visible discontinuity and the system of smaller ones that in fact form this large visible discontinuity. That is the question that should be in the focus of future research of the influence of discontinuities on ice navigation.

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