Influence of peculiarities of the form of a submerged body on the parameters of generated waves in the ice motion

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Abstract. It is known that when a submerged body moves under the ice surface in an ice cover, a system of flexural-gravity waves (FGW) appears, with a certain intensity of which it is possible to achieve partial or complete destruction of the ice. There are many theoretical works in which the submerged body is modelled in various ways, the influence of physimechanical properties, the depth of immersion and the length of the body on the stress-strain state of the ice cover is analysed. Similar works of an experimental nature are practically not encountered. An experimental study of the influence of the relative elongation of a submerged body and the depth of its immersion in under-ice motion on the deflection and curvature of the generated flexural-gravitational waves is performed. With the help of the proposed criterion of ice destruction, the ice-breaking capacity of the FGW was assessed.

1. Introduction

Today the process of development of flexural-gravity waves by the motion of a solid body under the ice cover near its surface is studied little. Normally, when solving similar tasks at the theoretical level an immersed body of a simplified form is used. Kheisin [1] studied the plane steady-state problem of the motion of vortex under a layer of broken ice. Bukatov and Zharkov [2] studied the steady motion of a point source of mass under a floating elastic plate and analyzed the effect of the velocity of motion, the depth of the source and the thickness of the plate on its deflection. In Pogorelova’s work [3] a SV was modelled by a source-sink system, moving in a fluid close to the surface of an elastic plate. In Sturova's work [4] the solution of the linear steady problem of the flow of nonviscous liquid around a sphere under the ice cover, broken ice, a membrane, and also under the free surface is performed. Korobkin [5] considers the nonlinear problem of non-stationary waves caused by the submerged elliptic cylinder, moving under the ice cover. In Pogorelova’s work [6] the influence of the thickness of the plate, the size of a submarine and its velocity on the amplitude of the deflections of floating plates is analyzed numerically. It has been shown theoretically that the wave formation in the ice cover and the efficiency of its destruction depend significantly on the relative elongation and displacement of the immersed body, as well as the speed of its movement and the depth of immersion.

In work on the basis of experimental studies, the influence of relative elongation and depth of immersion of a submerged body on the parameters of waves generated by it under the ice sheet motion is analyzed.
2. Equipment and technique for conducting experiments

Experimental studies of a submerged body motion under the ice sheet carried out in the ice tank laboratory [7] “Ice technology” in Solom-Aleikhem Primursky State University” (Birobidzhan, Russia). The main element of the tank is a bowl with the dimensions $L \times B \times H = 14 \times 3 \times 1$ m, equipped with a rail with a towing carriage which allows a model submerged body to be towed. The pool tank is a welded construction reinforced with ribs installed on the foundation and covered with a layer of insulation. To prevent ice on the inner surface of the sides of the tank heating elements are fixed on the outer wall surfaces. The ice tank is equipped with a system for collecting and model ice melting.

![Figure 1. General view of the ice tank.](image)

Due to the lack of refrigerating machines, experimental studies were carried out only in the winter period (December-January). The model of the ice cover was made in the ice basin by freezing natural freshwater without any dopant up to the set thickness (0.002 m) in natural conditions. The room where the basin is located was not heated for the entire period of the experiment. The experiments were carried out only at night time from 9.00 p.m. to 5.00 a.m. At night there were negligible fluctuations in the room temperature, within the difference of 1°C to 2°C, although the room temperature varied from -10°C to -18°C, depending on the outside temperature, varying from -25°C to -30°C. Relatively uniform ice sheets were thus obtained in 1-1.5 hours at night, except for the patches of thaw on the ice. Effects of snow and wind from the outside were minimized at the ice basin. Due to a layer of insulating material installed on the sides and under the bottom of the basin and compliance with constant temperature mode, the thickness of the ice at the walls of the basin and in the middle of the ice field did not exceed 0.0005 m. After carrying out of each model test, broken ice pieces were removed and the depth of the model was readjusted, and then ice sheet was formed. To conduct the experiments necessary equipment and measuring system to register vibrations of model ice was prepared. By towing the model vessel its velocity and profiles of FGW were determined. The towing system allowed carrying out model tests at velocities of up to $u_{sv} = 2.4$ m/s under steady motion conditions. The time of motion of the model after starting work at stationary regime did not exceed 4 sec.

To carry out model experiments models of submerged bodys were made at a scale of $\lambda_l = 1:120$ was made as drop-shaped body of rotation, length-diameter ratio $L_{sv}/B_{sv} = 8.4-11.4$ (where $B_{sv} = 0.12$ m). The parameters of the model were chosen considering previously executed experimental studies [8] in view of modeled ice conditions these parameters are optimal.

Harnessing of the model in the towing system was made through carabiners connecting the tow cable with attachment points located in the extremities of the body.

Simulation scale equal was selected basing on the size of the ice pool, with the length of the channel providing access to the steady motion of the model SV. The width was sufficient to eliminate
the influence of the waves reflected from the channel sides, on the principle wave system [9]. Modelling of sea ice cover can be executed by using various ice models and for each of them there are corresponding conditions of similarity. The usual modelling is performed with partial satisfaction of conditions of similarity [10]:

\[ \lambda_E = \lambda_w = \lambda_h \]

(1)

where \( \lambda_E \) is the model scale for Young’s modulus; \( \lambda_w \) is the model scale for deflections; \( \lambda_h \) is model scale for ice thickness.

In this case, the requirements for similarity conditions with respect to Poisson’s ratio \( \mu \) and density \( \rho \) of the model ice are satisfied.

The model vessel must be geometrically similar to the real one and their displacements must be in proportion to the cubed modulus of the geometrical scale-ratio:

\[ \frac{L_n}{L_m} = \lambda_l, \quad \frac{D_n}{D_m} = \lambda_l^3, \]

(2)

where \( L_n \) is the length of the full-scale vessel; \( D_n \) is the model vessel displacement.

The model motion velocity \( u_m \) is determined by the condition of similarity:

\[ \frac{u_n}{u_m} = \lambda_l^{1/2}, \]

(3)

where \( u_n \) is the full-scale vessel velocity.

The parameters of the model FGW are converted to natural ones in accordance with the modulus of geometrical similarity:

\[ \frac{\lambda_n}{\lambda_m} = \frac{w_n}{w_m} = \lambda_l \]

(4)

where \( \lambda_n \) is the length of the full-scale FGW; \( \lambda_m \) is the length of the model FGW; \( w_n \) is the full-scale FGW deflections; \( w_m \) is the model FGW deflections.

When natural ice cover is used as model one, the thickness of the modeling ice will be calculated when converted to natural one in accordance with the following relations:

\[ h_n = h_m \lambda_l^{4/3} \left( \frac{\sigma_n}{\sigma_m} \right)^{1/3}, \]

(5)

where \( h_n \) is the natural ice thickness; \( h_m \) is the modeled ice thickness; \( [\sigma_n]_n \) is the natural flexural stresses; \( [\sigma_m]_m \) is the modeled flexural stresses.

Determination of flexural strength of the model ice was experimentally performed by testing beams and for that purpose the model ice cover was prepared by building up ice of the required thickness \( h_m=0.002 \) m [11]. The beams had a rectangular shape with the parameter of \( l \times b = 0.15 \times 0.45 \) m which were prepared in the model ice by cutting out according to the stamp by the rotating Dremel tool. The force required for beam destroying was determined by using the electronic dynamometer Mark - 10 (USA) (Fig. 4) (Kozin et al. 2016). The average value of the flexural strength for natural ice was the value of \( [\sigma_n]_n=0.7 \) MPa, value of the flexural strength for model ice was of \( [\sigma_m]_m = 1.75 \) MPa. The thickness of the modeling ice cover after conversion to natural one was \( h_n=1.6 \) m.

It is known that at modeling sea ice by using fresh-water model ice, modulus of elasticity of the natural ice should be less then modulus of elasticity of the model ice \( E_n > E_m \) however the ratio \( E/\sigma_n \) for sea ice is practically the same as that for fresh-water ice. To meet this condition at modeling ice is very important [12]. To enhance the visibility of fractures of ice, the model ice surface was covered with a thin layer of snow, soon after the model field formation.

The coefficient \( \alpha \) was used as a criterion for breaking model ice, that is it is equal to the maximum value of the tangent of the surface slope of the ice plate. The relationship between failure of ice cover and the coefficient \( \alpha \) was already empirically determined in Kozin’s experimental work [10]. It was stated, that for the load motion over the ice cover as well as for motion of a submarine vessel when the
maximum value of the slope of the ice surface is greater than the value of 0.04, it leads to complete ice failure and cracks opening. The value of $\alpha$ in experimental studies was defined by the formula:

$$\alpha=2\pi w_m/\lambda_m. \tag{6}$$

Due to the complexity of the study, the duration of the preparation of the model ice field and limited cold period (December-January), aiming to identify optional parameters of the experiment such as model displacement velocity, relative deepening and water depth a series of preliminary test model runs was executed. According to the performed study the most significant results to be expected at velocity of the model vessel equal to $u_m=1.42\pm2.17$ m/s, model deepening equal to $h_{svm}=0.16\div0.25$ m.

3. Results of the model experiments

Figs. 2-5 show the main results of model experiments. The maximum values of the deflection of ice were taken at a critical speed of the load, which amounted to $u_m=1.85$ m/s.

From Figs. 2 and 3, it follows that the critical velocity are great enough. The value of the critical velocity did not depend on the parameters of the models and the depth of immersion.

The maximum destruction rate of model ice was reached when moving at a critical speed (Figs. 4-5).

The nature of the destruction of model ice after passing through the load is shown in Figs. 6-8. Movement at subcritical speeds led to a significant decrease in the area of destruction of model ice (Fig. 6). At velocities above the critical value, the fracture area increased, but there was no intensive destruction of ice and grinding of ice floes. It can be seen from the graphs that an increase in the relative elongation of a submerged body leads to a decrease in the ice-breaking ability of flexural-gravitational waves, since their curvature drops (Fig. 7). With increasing depth, the deflections of model ice (Fig. 3) and the curvature of the FGW (Fig. 5) are also significantly reduced.

Figure 2. The relationship of the deflections $w_m$ at different submerged body velocity: №1 $L_mB_m=8$; №2 $L_mB_m=9.9$; №3 $L_mB_m=11.4$. 

![Figure 2](image_url)
Figure 3. The relationship of the deflections $w_m$ at different the depth of submerged body $L_m/B_m=8$: №1 $h_{svm}=0.16$; №2 $h_{svm}=0.21$; №3 $h_{svm}=0.25$.

Figure 4. The relationship of the coefficient $\alpha$ at different submerged body velocity: №1 $L_m/B_m=8$; №2 $L_m/B_m=9.9$; №3 $L_m/B_m=11.4$. 
Figure 5. The relationship of the coefficient $\alpha$ at different the depth of submerged body $L_m/B_m=8$: №1 $h_{svm}=0.16$; №2 $h_{svm}=0.21$; №3 $h_{svm}=0.25$.

Figure 6. The nature of the destruction of model ice after passing through the load ($L_m/B_m=8$, $h_{svm}=0.16$ m, $u_m=1.85$ m/s, $h_m=0.002$ m).

Figure 7. The nature of the destruction of model ice after passing through the load ($L_m/B_m=8$, $h_{svm}=0.16$ m, $u_m=1.42$ m/s, $h_m=0.002$ m).
Figure 8. The nature of the destruction of model ice after passing through the load \((L_m/B_m=11.4, h_{svm}=0.16\, m, u_m=1.66\, m/s, h_m=0.002\, m)\).

4. Conclusion

The results of the studies show that the depth of submerged body and ratio length-diameter has a significant impact on the parameters of FGW. The maximum values of the deflection of ice were taken at a critical speed of the load, which amounted to \(u_m=1.85\, m/s\). Change the depth and ratio length-diameter area of the body do not lead to a decrease in the critical velocity.

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