Influence of the Shape of a Submarine Vessel on the Ice Breaking Capacity of Flexural-Gravity Waves

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Abstract. The severe climatic conditions of the Arctic Regions impose great constraints on traditional methods of hydrocarbon extraction. That is why underwater technologies used for raw material extraction and handling are very promising. The influential factor for the safe operation of an submarine vessel (SV) during under-ice navigation is breaking the surface through the ice cover. The traditional method of coming to the surface does not always apply because of the difficult and dangerous maneuvering and ice partial depth of the broken ice. In fact, the load that arises in the ice moves generates a system of progressive flexural-gravity waves (FGW). In case the waves are intensive to a certain extent, the ice of heavy thickness can destruct. The paper informs on an experimental study of FGW ice-breaking capacity generated due to SV of different projects running. The experiments were conducted in an ice tank. The ice destruction efficiency is determined using the ice-breaking criterion. The authors conclude that the principal factor affecting the ice-breaking capacity is not the displacement of water, but a fineness ratio of a submarine ship, as well as a cross-section ship shape. The subject of the influence of the vessel depth on FGW characteristics is explored.

1. Introduction
The use of traditional hydrocarbon production methods and technologies in the severe climatic conditions of the Arctic is very limited. The deposits are often located far from the coastline. Therefore, there is little developed transport infrastructure. Due to the long cold winter, the thickness of the ice cover comes up to two or more meters. The main disadvantage of the super marine method of exploitation marine fields at subarctic and arctic conditions is their technical and economic inexpedience in ice-rich years. For many years, design engineering centres have suggested various options for using transport submarines as means for field exploitation, support and shipment of hydrocarbons [1].

The use of subsea industries is the most advanced. It is based on the use of underwater well injection systems. The well mouths are located at the sea bottom. Subsea development can be completely autonomous, as well as combined with fixed or floating processing platforms. In comparison with traditional methods, this method is appropriate to consider as the central one for the development of Arctic hydrocarbon resources. So, the Iceberg project built by the Central Design Bureau for Marine Engineering “Rubin” was presented at the Neva-2017 exhibition in 2017 [2]. The Iceberg project includes the undersea drilling facilities for the construction of extraction wells. The facilities provide
drilling operations in a robotic mode. The project involves the construction of two civil manned nuclear-powered submarine ships. The first vessel is an underwater transport and installation unit for the tool moving-in, support, installation and dismantling. The second underwater vessel is designed for undersea seismic acquisition and monitoring. Even though the execution of such development projects contributes to the development of technologies in the field of oil-and-gas extraction in the severe Arctic climate, the use of submarines detached from the Navy is supposed to be the most perspective [3].

The key factor that ensures the safety of submarine vessel operation during ice navigation is the capacity of the vessel to break the surface in the ice cover. As a matter of fact, in case of emergency when coming to the surface can be poorly controlled, and the floating speed far exceeds critical standards, and impact blow on the bottom of ice can lead to the destruction of the ship bow section, the sea cabin, subsequent loss of containment, stability loss and a wreck of a ship.

It is known that when a submerged body moves near the bottom of the ice, it results in a system of flexural-gravity waves in the ice cover. It is possible to destruct the ice partially or completely if there is a certain intensity of FGW [4]. The maximum thickness of ice destructed by resonant FGW is much higher than that during the static break of the ice cover during the surfacing by the traditional method, while there is a minimum-energy ice cracking [5].

The theoretical [6, 7] and experimental [8, 9] studies performed by different scientists have shown a high ice-breaking capability of FGWs generated by a moving load. Nevertheless, a very interesting task is to assess the effectiveness of FGW ice destruction because of the movement of submarine vessels with characteristics and the architecture of near-recent submarines. In the research [IOP], the authors evaluated the FGW ice-breaking capability generated due to the movement of models of SV of projects 949A, 971, 667BDRM. A compound shape of the submarine hull was replaced by a simplified one in the form of structures of rotation of an irregular shape with a displacement and a fineness ratio kept. The volume of the projecting parts was distributed throughout the entire volume of the models.

In the presented study, the researchers carried out an experimental assessment of FGW ice-breaking capacity generated due to the movement of SV models of different projects with their architectural features kept.

2. Equipment and technique for conducting experiments

The ice tank of the laboratory of ice technology at Sholom-Aleichem Priamursky State University (Birobidzhan, Russia) [10] with dimensions 14 × 3 × 1 m was used to carry out the model experiments.

Three projects of modern submarine operating in the Russian Federation were selected as demonstration models. The characteristics of the models are shown in Table 1. All three projects have different hull shapes, including cross-sections along with the midship frame, fineness ratio and displacement. The main dimensions and architectural features of the vessels were chosen according to the study of Apalkov [11]. The models were made by a layer-wise printout of a physical entity using a digital 3D model. The Raise3D printer was used. The modeling scale was 1:120.

| Submarine project | Model Number | $D_{m}$, kg | $L_{m}$, m | $B_{m}$, m | $L_{m}/B_{m}$ |
|-------------------|--------------|-------------|------------|-------------|---------------|
| 971               | 1            | 7.9         | 0.925      | 0.115       | 8             |
| 949A              | 2            | 14.5        | 1.275      | 0.152       | 8.4           |
| 667Б              | 3            | 10.5        | 1.3        | 0.097       | 13.4          |

An unmanned towing carriage and a cable towing system were used to take the models in tow. The wave surface was recorded through a Q. Bloxx A107 robot measuring system using noncontact laser sensors LAS-Z Q. Gate A107 by Way Con (Germany).

The modeling scale is selected based on the thickness of the model ice and the size of the ice tank, while the length of the tank provided access to the steady run of movement of SV models. The width of
a bowl is enough to exclude the influence of waves reflected from the channel side frames of the channel towards the basic wave system at the moment of breaking and crack opening in the model ice [12].

A model of natural pure ice was used when carrying out the experiments on the movement of SV models under the ice cover. An opportunity of using natural ice as a model, although it is extra-heavy, is described in the paper [13]. Free cooling was used for ice freezing. The experiments were carried out at night in the cold season at steady temperatures below zero. The thermostatic control system indoor allowed keeping the temperature constant. It constituted a model ice field of a given thickness $h_m = 2\text{ mm}$ for 30-45 minutes, depending on the indoor temperature from -10 to -20°C below zero.

Ice modeling was carried out with a partial fulfillment of the similarity conditions according to the paper [5].

The thickness of the simulated ice cover was determined from the dependence:

$$h_n = h_m \lambda_m^{4/3} \left(\frac{[\sigma_u]_n}{[\sigma_u]_m}\right)^{1/3}$$

where $[\sigma_u]_n$ is the cross-breaking strength of the natural ice [14]; $[\sigma_u]_m$ is the cross-breaking strength of the model ice.

The bending strength of the model ice was determined experimentally by testing the bearers floated according to the recommendations in the studies [15].

When freshwater ice is used for modeling sea ice, Young’s modulus of pilot ice should be less than the model $E_n > E_m$. The $E / \sigma_u$ correlation for sea and freshwater ice is nearly the same, and it is extremely important to observe this term in modeling [16].

The coefficient $\alpha$ was used as a criterion for ice breaking, showing the dependence of the slope angle of the ice plate and its destruction. It was found in [5] that when the load moved on the ice, the submerged object moved under the ice, and if the maximum value of the slope angle of the ice surface exceeded the value of 0.04, then cracks opening and ice breaking were observed. Since the model experiments were conducted using freshwater ice, its use for assessing the destruction of sea ice was not totally correct. However, the strength and crack resistance of sea ice are lower than that of freshwater. Therefore, the value $\alpha$ for sea ice should take smaller values. The value $\alpha$ was determined by the dependence $\alpha = 2\pi w_m / \lambda_m$

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where $\lambda_m$ is the length of model FGW; $w_m$ is the model FGW deflections.

3. Results of the model experiments

The test results of model 1 for different submergence values are shown in figures 1-2. When the submergence of the model increased, the deflection values began to decrease considerably. Thus, when the submergence depth was $h_{svm}=0.21$ m, the ice deflection decreased by 18-53% compared to the submergence depth $h_{svm}=0.16$ m (figure 1). The FGW ice-breaking capacity, i.e. the values of the coefficient $\alpha$, decreased by 17-45% (figure 2). When the submergence was $h_{svm}=0.25$ m, the deflections decreased by 48-81%, and $\alpha$ decreased by 43-78%. Ice destructed only at the rates which were near-critical (figures 3-4). There were only longitudinal main ice cracks, but there was no disintegration of ice cover.
Figure 1. The dependence of deflections of the model ice on the rate of movement of model 1 when submergence is: No.1 $h_{svm}=0.16$ m; No.2 $h_{svm}=0.21$ m; No.3 $h_{svm}=0.25$ m.

Figure 2. The dependence of coefficient $\alpha$ on the rate of movement of model 1 when submergence is: No.1 $h_{svm}=0.16$ m; No.2 $h_{svm}=0.21$ m; No.3 $h_{svm}=0.25$ m.

Figure 3. The fracture pattern of FGW model ice due to the movement of model 1 at the rate of $u_m=1.61$ m/s at $h_{svm}=0.16$ m.

Figure 4. The fracture pattern of FGW model ice due to the movement of model 1 at the rate of $u_m=1.61$ m/s at $h_{svm}=0.21$ m.

Figures 5-6 show the test results of model 2. The values of the FGW ice parameters decreased when the submergence value increased. If the submergence depth was $h_{svm}=0.21$ m, the ice deflections decreased by $17\div47\%$ compared to the submergence depth $h_{svm}=0.16$ m (figure 5). FGW ice-breaking capacity decreased by $21\div45\%$ (figure 6). When the submergence depth was $h_{svm}=0.25$ m, the deflections decreased by $34\div71\%$, and the values of the coefficient $\alpha$ decreased by $43\div76\%$. The rate of the deflection curve changed according to the submergence (figure 5). So, if there was minimum submergence, the dependencies were flatter. When the submergence depth increased at the near-critical rates, a more sudden increased of the $w_m$ values appeared. It dealt with the peculiarity of the influence of the ice cover and the lift force while moving the lift force on the nature of the model motion.

The fracture pattern of the model ice for different rates of movement of model 2 is shown in figures 6-7. There is a disintegration of ice cover and ice raft crush when the carrying capacity of ice cover at all rates covered is completely lost. When the model submergence was $h_{svm}=0.21$ m, the disintegration of ice cover at the rate range $u_m=1.66\div2.17$ m/s was preserved. When submergence increased up to $h_{svm}=0.25$ m, the ice rafts crushed only at near-critical rates.
The test results of model 3 test are shown in figures 9-10. It can be seen from the dependencies that when the submergence depth increased, the values of FGW parameters decreased greatly.
When the submergence depth was $h_{sw}=0.21$ m, the ice deflections decreased by $27\div56\%$ compared to the submergence depth $h_{sw}=0.16$ m (figure 9). FGW ice-breaking capacity decreased by $23\div52\%$ (figure 10). When the submergence depth was $h_{sw}=0.25$ m, the deflections decreased by $41\div62\%$, and $\alpha$ decreased by $49\div66\%$.

Projecting parts did not influence much the efficiency of ice destruction for model 3. The ice raft crush was not recorded even at near-critical rates. As a matter of fact, the destruction of the FGW ice cover for models 3 is not effective because of small displacement $D_m$ and a large fineness ratio $L_m/B_m$.

4. Conclusion

According to the obtained results, the authors can make the following conclusions:

- Quite effective ice destruction can occur due to the movement of SV of 971 project. Despite the minimum displacement among all the studied projects, the submarine has a small fineness ratio. It results in the FGW ice-breaking capacity development, which is rather high. However, as the experiments prove, the disintegration of ice cover can occur when the vessel is not more than 20 m deep.

- The most effective use of FGW ice-breaking capacity is due to the movement of SV of 949A project. They have ample displacement to destruct ice thickness of more than 1.5 m at a depth of more than 25 m and a complex geometric ship form. As the experiments show, it also contributes to the wave development greatly.

- FGW ice destruction for SV of 667 BDRM project is possible if submergence is no more than 15 m. The experiments have shown that due to a large fineness ratio, despite quite a large displacement, the curvature, and therefore, the ice-breaking capacity of generated FGWs is not enough for ice cracking.

5. References

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