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MODEL INVESTIGATIONS OF WAVE FORMATION IN SOLID ICE COVER FROM THE MOTION OF A SUBMARINE

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One of the most promising ways of solving the problem of the all-year-round use of northern sea channels is to construct a submarine transport fleet capable of overcoming ice obstacles under water. The conditions under which such ships could be used must obviously provide for the possibility of emergency surfacing into the continuous ice cover. The technology of such surfacing at the present time consists of the static downward loading of the ice plate by producing a positive residual buoyancy by draining the main ballast tanks after preliminary blasting of the ice in the region where surfacing occurs. Experience in the practical use of such surfacing on Russian and foreign submarines shows that the conning tower is inevitably damaged as well as the structure of the upper deck, and often lightweight parts of the vessel also. These undesirable aftereffects can be avoided by partial or complete destruction of the ice cover by exciting flexural-gravitational waves of a certain amplitude in the ice [1]. To do this the vessel floats up to a safe depth and moves under the ice at a certain speed. Flexural-gravitational waves develop in the ice cover, at a certain intensity of which the ice cracks or completely fractures. The vessel then returns to the region where the flexural-gravitational waves act on the ice and surfaces in the weakened or broken ice. This surfacing technology is accompanied by noise, the frequency spectrum of which is close to the natural frequency spectrum. Hence, this kind of surfacing of submarines also increases their secrecy.

The fracture of the ice by flexural-gravitational waves can occur both during the motion of water-displacing ships [2], and of amphibious hovercraft. In the first case the vessel moves along the edge of the ice or in a channel, exciting a system of ship waves, which are then converted into flexural-gravitational waves. When the vessel reaches a certain speed the amplitude of the flexural-gravitational waves increases to the maximum values and the ice cover of corresponding thickness begins to break up over a considerable area (the width of the fractured strip for the motion of average ice breakers can reach hundreds of meters [3]). In the second case, amphibious hovercraft move with the resonance speed over the ice [4]. The excited system of flexural-gravitational waves for a certain mass of the vessel also leads to break-up of the ice cover over a large area.

In this paper we consider model investigations of the excitation by submarines of flexural-gravitational waves with an amplitude sufficient to break up ice cover of actual thickness at safe depths. Among the theoretical publications devoted to this problem we may mention the investigations carried out by Kheisin [5]. Taking as a basis the solution obtained by Kochin for a free surface, he considered the plane problem of the motion of a body under ice. A qualitative analysis of the nature of the excited flexural-gravitational wave was given in [5]. A theoretical solution of the problem in a three-dimensional formulation is extremely difficult.

The purpose of the present paper is to investigate how the parameters of the flexural-gravitational waves depend on the speed, depth of immersion, and size of the ship, and also to estimate the ice-breaking possibilities of ships by converting the data obtained from ice-breaker tests to nature using the criteria obtained.

Formulation and Solution of the Problem. We will use the possibility of modelling flexural-gravitational waves on floating elastic films [6]. In this method the modelling scale k is determined by the modulus of elasticity of the material, which simulates solid ice: $k = E_N/E_M$, where E_N and E_M are the moduli of elasticity of natural and model ice. Then, using the theory of dimensions, the modelled and natural parameters are connected by the relations

$$\frac{w_N}{w_M} = \frac{\lambda_N}{\lambda_M} = \frac{h_N}{h_M} = \frac{L_N}{L_M} = \frac{B_N}{B_M} = k,\ \frac{v_N}{v_M} = \frac{T_N}{T_M} = \sqrt{k},$$
$$\frac{D_N}{D_M} = k^3,\ \frac{v_N}{\sqrt{gL_N}} = \frac{v_M}{\sqrt{gL_M}},$$

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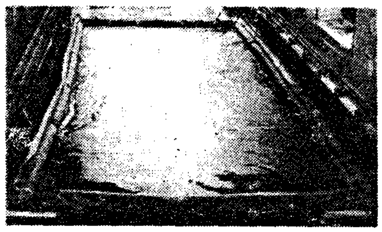

Fig. 1

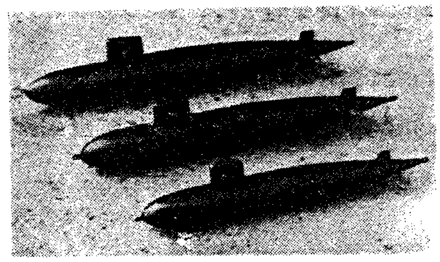

Fig. 2

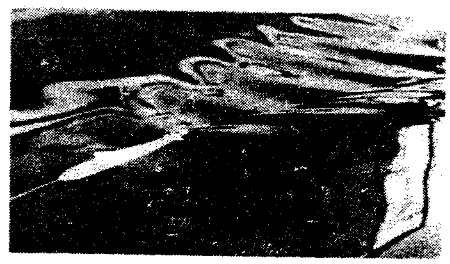

Fig. 3

where w_N and w_M are the sag of the ice, λ_N and λ_M are the wavelength of the flexural-gravitational waves, h_N and h_M are the thickness of the ice, L_N, L_M, B_N and B_M are the length and width of the ship, v_N and v_M are the speed of the ship, T_N and T_M are the period of the flexural-gravitational waves, D_N and D_M are the displacement of the ship, and g is the acceleration due to gravity.

We used a polymer film (PVC plastic) as the model ice. This stimulated ice with a thickness of $h_N = 0.2$ m. The modulus of elasticity of the plastic E_M is determined experimentally as a function of the rate of deformation. To produce positive buoyancy (the density of the plastic $\rho_M = 1400$ kg/m^3) the film was fastened along its perimeter to a hoop (Fig. 1). Although there was some difference between Poisson's ratio μ_M and the density ρ_M of the plastic and those of natural ice, as can be seen from experiments on the excitation of flexural-gravitational waves by a moving load, this has practically no effect on the wave parameters.

Experiments were carried out in an experimental tank with dimensions of $45 \times 4 \times 3$ m provided with a gravitational towing system. The dimensions of the model ice field were 6×3 m. A general model of modern foreign submarines with a relative length $L/B = 8$ and an overall fullness factor $\delta = 0.52$ was taken as the submarine. To estimate the effect of the scaling on the parameters of the flexural-gravitational waves we constructed three models (Fig. 2) to a scale of $k = 1/200$, which corresponds to the displacement of natural ships: 3500, 6000 and 9000 tonnes. The vessel was towed both under the model ice, and under pure water conditions (Fig. 3) at relative depths of $h_0/L = 0.2$-0.7 (h_0 is the depth of immersion of the model). The parameters of the flexural-gravitational waves (the wavelength and amplitude) were recorded by a displacement pickup at different points of the model field and were recorded on a two-coordinate plotter. Figure 4 shows the overall form of the deformations of the model ice, recalculated to natural conditions (the bending of the ice has been plotted along the vertical axis and the distance, as a multiple of the length of the ship, along the horizontal axis).

Systematic towing of the models enabled us to determine the speed at which the amplitude of the excited flexural-gravitational waves reaches its maximum values. The value of this critical (resonance) speed is close to the theoretical value of the critical phase velocity of flexural-gravitational waves for deep water [5].

$$v_p = \sqrt{\frac{Dg^2}{\rho_i h}}.$$

Here D is the cylindrical stiffness of the ice plate, ρ_i is the density of the ice, and h is the thickness of the ice.

From the results of the towings we obtained a graph of v_p as a function of the depth (Fig. 5). The mean value of v_p is about 17 m/sec, while the theoretical value for $h = 0.2$ m is 15.8 m/sec. The dimensions of the models have no effect on v_p in this case. It can be seen from Fig. 6, where we show the profiles of the flexural-gravitational waves for different speeds

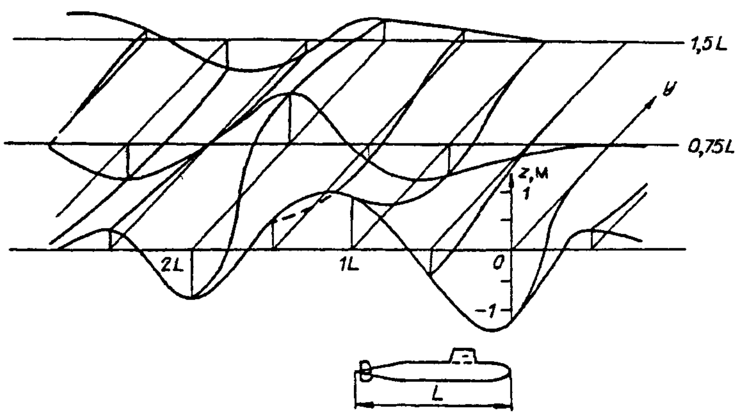

Fig. 4

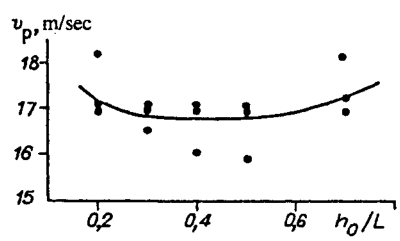

Fig. 5

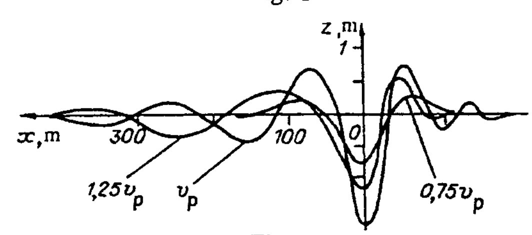

Fig. 6

of the model (the deformation of the ice for a section y = 0 is plotted along the Oz axis), that as the speed approaches v_p an considerable increase in the amplitude of the flexural-gravitational waves is observed. For a fixed wavelength this leads to an increase in the curvature of the profile of the flexural-gravitational waves and correspondingly of the bending stresses. Complete attenuation of the waves is observed at a distance of 3-4 wavelengths of the flexural-gravitational waves.

Comparing the parameters of the gravitational waves on a free surface and the flexural-gravitational waves at the same depths at resonance speeds of the model, we can conclude that the presence of ice leads to a unique containment of the volume of liquid.

Thus, the amplitude of the flexural-gravitational waves under the same conditions is 20-30% greater than the amplitude of gravitational waves. An increase in the resistance as the model approaches under the ice field is also observed.

We can use the results obtained to estimate the ice-breaking capability of flexural-gravitational waves as a function of the depth at resonance speeds of motion. We will take as the criterion of complete fracture of ice the theoretical level of flexural-gravitational waves [7]. From the results of processing a large number of experiments on the fracture of natural ice by flexural-gravitational waves this level amounts to $2.1\sigma_N$, where σ_N is the elastic limit of ice for bending. A justification of this approach is given in [7].

We will now turn from the deformations of the model field obtained to the bending stresses. Since, in the region of the model, the profile of the flexural-gravitational waves is close to plane sinusoidal waves (Fig. 3), then, erring on the safe side (we reduce the level of stresses), the value of the flexural stresses can be estimated from the formula

$$\sigma_x = \frac{EAh}{2(1-\mu^2)}\left(\frac{2\pi}{\lambda}\right)^2 \sin\frac{2\pi x}{\lambda},$$

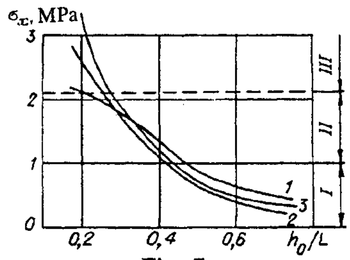

Fig. 7

where E is the modulus of elasticity of ice, A is the amplitude of the flexural-gravitational waves, λ is the wavelength of the flexural-gravitational waves, and x is the coordinate.

The results of calculations, presented in Fig. 7, show that vessels of the same relative length (L/B = 8) and different displacements produce practically the same level of stresses in solid ice when $h_0/L = 0.3$. Complete fracture of the ice, in accordance with the fracture criterion employed, can be expected for a relative immersion of $h_0/L = 0.2$-0.3 (region III), while the formation of cracks in the solid ice is possible at up to $h_0/L = 0.4$-0.5 (region II) for a resonance speed of the ship of $v_p = 17$ m/sec and the elastic limit of the ice employed and a bending limit $\sigma_N = 1$ MPa.

This research enables us to conclude that the resonance method of fracturing an ice cover can be achieved by submarines in order to surface in solid ice at safe depths of the vessel. This method can be employed to predict the ice-breaking capabilities of submarines and to develop recommendations to enable vessels to surface in solid ice.

REFERENCES

1. V. M. Kozin, "A multibodied submarine," Inventor's Certificate No. 1,233,401, Otkryt. Izobret., No. 19 (1984).
2. A. Ya. Ryvlin and D. E. Kheisin, Tests on Ships in Ice [in Russian], Sudostroenie, Leningrad (1980).
3. V. M. Kozin, "A method of breaking ice cover," Inventor's Certificate No. 1,605,471, Otkryt. Izobret., No. 41 (1990).
4. V. A. Zuev and V. M. Kozin, The Use of Hovercraft to Break Ice Cover [in Russian], Izd. DVGU, Vladivostok (1988).
5. D. E. Kheisin, Ice-Cover Dynamics [in Russian], Gidrometeoizdat, Leningrad (1967).
6. V. M. Kozin, "Modelling of flexural-gravitational waves in a solid cover," in: Theory and Strength of Ice-Breakers [in Russian], Izd. GPI, Gor'kii (1982).
7. V. M. Kozin, "The estimate of ice breaking capacity by a moving load," in: Proceedings of the 7th International Offshore Mechanics Conference, USA (1988).