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Experimental-analytical study of the platform "North Pole" stability under the conditions of intensive ice pressures

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ABSTRACT

Design of the first in the world ice resistant self-propelled platform of the ship type was developed in the Russian Federation for performing year-round scientific studies in the central Arctic Basin. Peculiarity of operation of this platform is its long drift in multiyear ice. Correspondingly, not only sufficient hull strength under the conditions of ice pressures should be provided, but also the platform stability.

At the design stage not only theoretical calculations of stability diagram were carried out but also studies in the AARI ice tank. For performing physical modeling of the platform behavior under the ice pressures a unique methodology was developed, according to which the platform model was subjected to the impact of approaching model ice floe from one of the sides. A measuring complex was installed onto the model, allowing us to measure with high frequency the platform heel and draft change in the process of interaction with ice. The obtained measurement data made it possible to calculate the ice heeling moment value and the main stability indicator – metacentric height – at each time moment

KEY WORDS: ice resistant self-propelled platform, ice model test, ice pressure, ice stability, ice heeling moment

NOMENCLATURE

IRSPP – ice-resistant self-propelled platform
BWL – Ballast waterline
DWL – Design waterline

INTRODUCTION

Continuous studies in the Arctic are determined by significant scientific and economic interests of Russia. However in connection with the manifested tendency for ice melting in the Arctic Ocean, long-term activities on the natural drifting ice floes are not safe at the present time and in some water areas, they cannot be carried out at all.

Construction of the unique floating structure – an ice-resistant self-propelled platform (IRSPP) "North Pole", performing functions of the drifting research station (Makarov et al, 2018) should serve as the efficient solution of this problem. The self-propelled platform will make it possible to address the entire range of scientific and exploration objectives in the Arctic sector, providing comfortable and safe conditions for the expedition members. The objectives could be fulfilled not only during the drift period but also at the time of transit to the place of the drift start, as the platform will be equipped with the own propulsion device and the hull shape will be close to that of ship.

Thus at the design stage of the IRSPP "North Pole" it is necessary to investigate both the active regime of the structure/ice interaction – ice performance and the drift regime in the ice massif, characterized by unavoidable ice pressures of different intensity.

Study of ice performance of the self-propelled platform can be carried out in the ice tank by the known methodologies applied for the models of ships and icebreakers (Shimansky et al, 1958). From the time of opening of the first in the world ice test tank (in 1955 at the AARI) a great deal of experience of conducting experiments was gained in this direction. The problem of ice pressures on ships was mainly investigated in terms of provision of strength of hull structures (Kheisin, 1962). For the IRSPP, study of stability under the conditions of ice pressures becomes primary, as the main operation regime is exactly a long drift in ice rather than forcing of the latter. As a result of the long drift at intensive compression, a massive ice "cushion" can be accumulated under the platform hull, consisting of different broken ice fractions, influencing stability of the floating structure. Besides, at pressure in multiyear ice of a large thickness, appearance of a capsizing moment is probable, occurring as a result of partial displacement of the hull and subsequent destruction of the ice floe edges under the sides.

To address the objectives set it is necessary to develop a methodology for conducting a model experiment, which will allow us to assess qualitatively and quantitatively the heeling moment and the change of the metacentric height of the IRSPP under the conditions of intensive ice pressures.

FACILITY UNDER TESTING

The IRSPP presents a ship with the hull shape optimized for a long drift under the ice conditions. The external view of the structure is presented in Figure 1a, and its characteristics in Figure 1b.

(a)

Characteristics	
Length by DWL	76.7 m
Breadth by DWL	21.8 m
Draft by DWL	8.60 m
Draft by BWL	7.64 m
Displacement by DWL	10390 t
Displacement by BWL	8821 t
Metacentric height	1.50 m
Ice cover thickness	0.8 ÷ 3.0 m
Ice floe drift speed	0.15 ÷ 0.50 m/s

(b)

Figure 1. The ice-resistant self-propelled platform “North Pole”:
(a) – external view of IRSPP; (b) – main characteristics of the IRSPP and parameters of ice conditions for modeling

During operation of the IRSPP the following variants of mooring to the ice floes are supposed: to the external edge of the ice floe on which the field camp will be deployed; in the natural fracture between the edges of ice floes; in the channel made by the icebreaker inside the ice floe.

At the impact of natural forces, causing intensive ice pressure, two scenarios can occur in the enumerated variants, determined in one case by equal ice thicknesses from both sides and in the other by different.

For modeling the described phenomena, the following arrangement of the experiment was employed (Figure 2). The model of the IRSPP is placed across the tank basin between two ice floes, one of which is frozen to the tank sides and has an excessive thickness and the other is mobile and thin. The mobile ice floe moves onto the model by means of the towing carriage. Due to such a solution, ice breaking occurs admittedly from the side of the thrusting floe and the model remains at the given place over the tank length. All processes we are interested in and typical of the scenarios considered, occur at this.

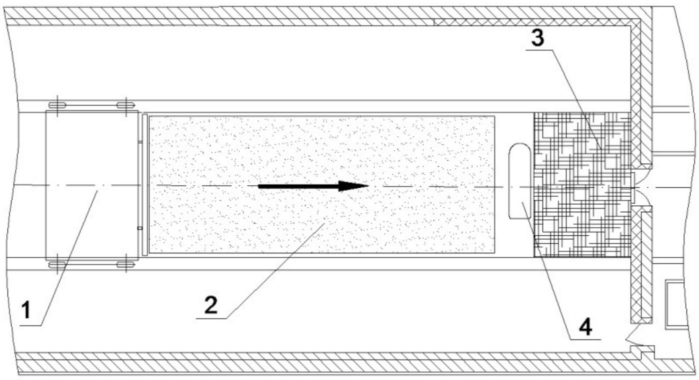


Figure 2. Scheme of conducting the model experiment on the ice pressures of the IRSPP:
1 – towing carriage; 2 – model ice floe; 3 – thickened model ice floe; 4 – platform model

As shown by the preliminary experiments, both scenarios are reduced to one common picture of facility interaction with ice. At pressure between the floes of different thickness the model rests against a thicker edge predetermining the ice destruction from the opposite side. At pressure in ice of equal thickness after a brief destruction of the edges alternatively from both sides the priority of breaking under one of the sides begins. In both cases one observes similar processes: periodic ice breaking accompanied by heeling and continuous accumulation of the broken out sectors near the model sides and extremities and also directly under the flat bottom in the form of the so-called ice “cushion”.

The model experiment is carried out in two stages. Preliminarily a test of model heeling in open water is carried out for determining the initial metacentric height h_0 and prescribing it the required value. For this, similar to the case of full-scale ship (Semenov-Tyan-Shansky, 1960), a sequence of known measures is performed, which mainly include the transfer of the parliament heel from one side to the other for creating heeling, which is fixed after the end of possible oscillations of the model relative to a new equilibrium position. The determination of the metacentric height is performed by the following formula (Semenov-Tyan-Shansky, 1960):

$$h_0 = \frac{pl}{D_0 tg\theta} \quad (1)$$

where p – parliament heel weight; l – distance from the parliament heel gravity center to the diametric plane of the model; D_0 – initial displacement; θ – heeling angle.

Setting the required value h_0 is achieved by redistribution of the main ballast inside the model towards the increase or decrease of the model gravity center z_g. As shown above, the model itself acts as a measuring tool. Therefore, the metacentric height will be a characteristic of sensitivity of this "instrument". From this position the underestimating of value h_0 increases the response of the model to the external capsizing moment, which in turn, allows us to obtain a greater accuracy in measuring the heeling angles in the process of the next stage of the experiment. However it is preferable to set h_0 proportionately to the full-scale value to preserve similarity of the interaction picture to real conditions at observing the other requirements (Sedov, 1981).

The second and the main part of the experiment is carried out under the ice conditions. The towing carriage moves the model ice floe onto the transversely oriented model. The thrust speed V_d and ice thickness h_i are prescribed in accordance with the requirements of model full-scale conditions and are recorded continuously in the process of the entire experiment. A fragment of implementation of this scheme in the AARI ice tank is given in Figure 3.

Inside the model hull, a six-component inertial module is installed, which makes measurement of projections of vectors of linear acceleration and angular speed to the orthogonal axes of the model coordinate system. The latter allows us to obtain the change of the model setting – in this case of draft and heeling – during the entire time of impact.

TESTING OF THE METHODOLOGY AND EXAMPLES OF THE RESULTS

According to the presented methodology, a series of 29 experiments on pressures exerted on the model of the "North Pole" platform was performed. Figure 3 presents fragments of the experiments, where the model is subjected to a heeling moment at pressures in ice (a), and the initial stage of formation of the ice "cushion" on the flat bottom (b) is also shown.

(a) (b)

Figure 3. Fragments of the experiments on the assessment of the ice heeling moment

In the course of trials of the IRSPP model in accordance with the methodology, the critical values of the heeling moment and losses of the metacentric height were obtained. The former comprised 4300 t·m for full-scale conditions at pressures of thick ice with a thickness close to 3

m. The maximum losses of the metacentric height comprised 30 % of the initial value of about 2 m and for the case of formation of the ice “cushion” in ice with a thickness of about 2.5 m.

PHYSICAL PICTURE OF INTERACTION

In the framework of the chosen scheme of conducting the experiment let us consider in detail a physical picture of interaction of the platform model with ice to identify the main and reject the secondary factors, determining the external impact.

After the contact with the model ice floe the gradual model displacement occurs practically at once (Figure 4a). This is determined by the fact that the hull has a significant flare angle even in the midbody (up to 15°) and the model ice conditions correspond to ice pressures in thick multiyear ice.

The process of displacement ends with destruction of the overriding ice floe edge. After this the model is rapidly submerged with a simultaneous heeling towards the side that destroyed ice (Figure 4b). At further thrusting the partly broken sector turns and submerges under the ice floe, and the “fresh” edge that arrived comes into contact with the hull predetermining the next cycle.

After some time the submerged broken ice reaches a significant size, which contributes to its further spreading beneath the flat bottom (Figure 4c). Ice accumulation occurs up to appearance of submerged ice from the opposite side. In the end the ice basin completely covers the underwater part of the hull (Figure 4d).

The formation of the basin is continuously accompanied not only with the transverse but also with the longitudinal model oscillations. The trim difference at this is completely determined by the non-simultaneity of destruction of the overriding floe edge along the model and also by the non-uniform distribution of broken ice under the hull by length. However the ice moments in the longitudinal plane do not present a serious danger for the platform and therefore are not further taken into account.

As can be seen from the description, the study process is oscillatory in general consisting of repeated cycles, differing from each other with time. The main factors determining this complex process: ice pressure, destruction of ice floe edges and formation of the ice basin under the hull.

Let us determine the forces (responses) and moments, acting on the model as a result of the enumerated causes.

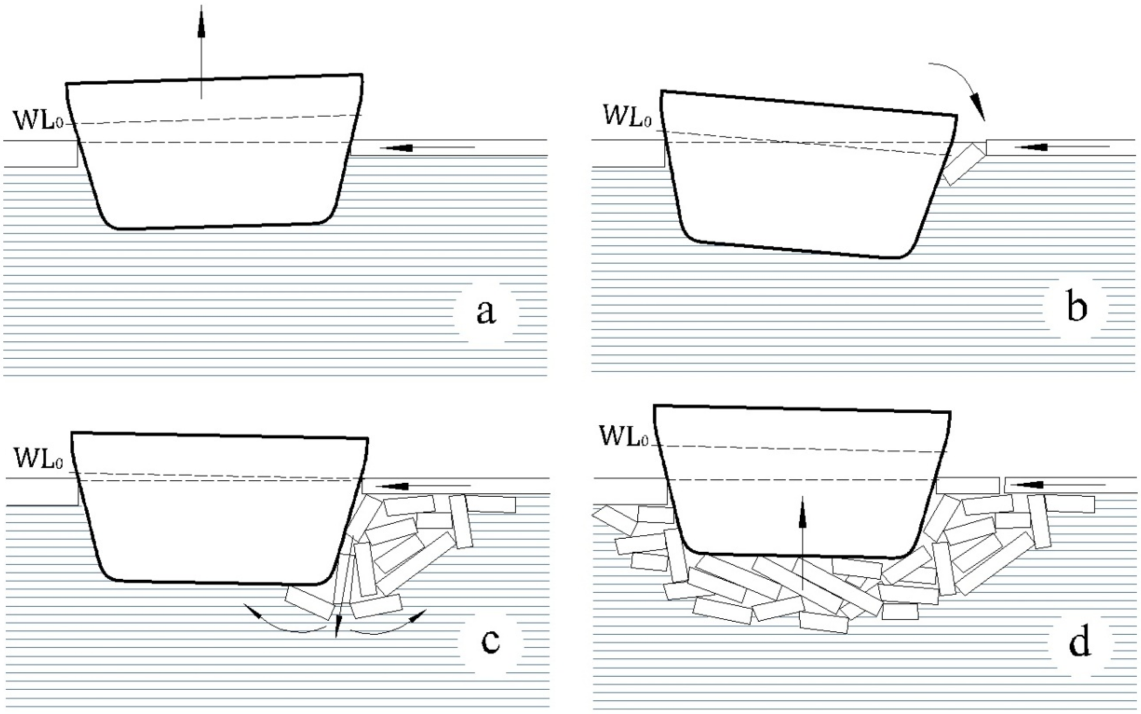


Figure 4. Main stages of interaction of the platform model with an ice floe at pressures

THEORETICAL METHODOLOGY GROUNDS

Displacement of the model at ice pressure acting in the horizontal plane, occurs due to vertical component responses *R*, occurring from the sides (Figure 5a). With surfacing, the share of vertical projections increases in connection with the displacement decrease by the value of ΔD.

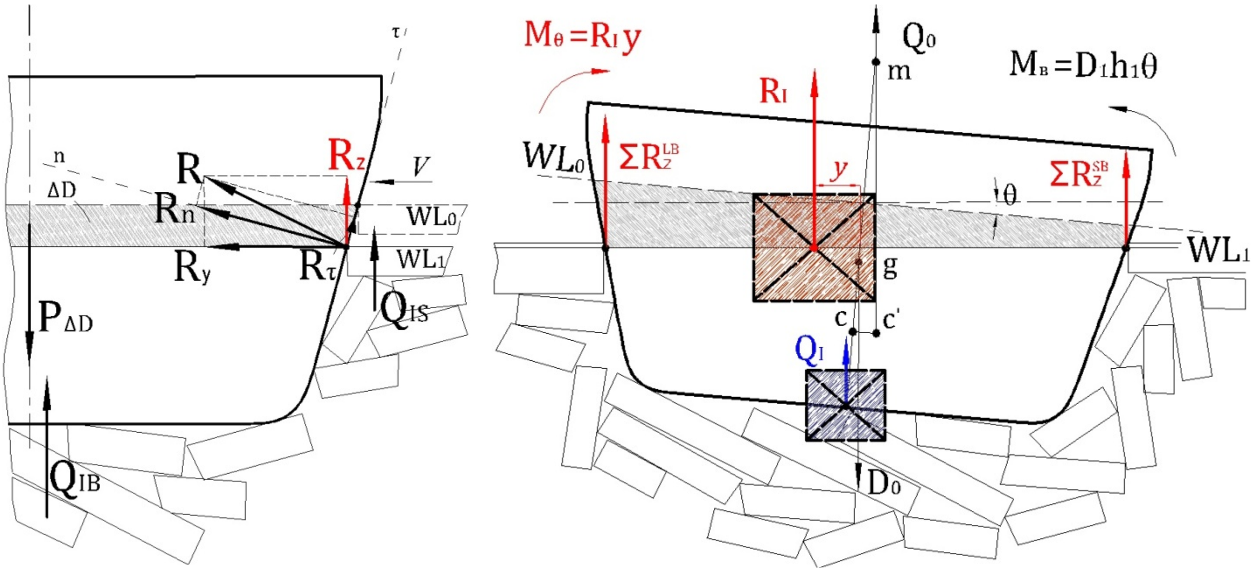
Destruction of the overriding ice plate occurs as a result of a complicated flexure (Kheisin, 1962) at the moment the vertical load exceeds the lifting capacity of the ice cover. Then under the action of the gravity forces, the model tends to the initial equilibrium position with the difference in the value of responses by sides, which results in the heeling position of the model.

The buoyancy force from the growing submerged ice under the side gradually leads to decreasing amplitudes of oscillations in each pressure cycle due to their damping. At the stage of formation of full value ice basin the total buoyancy force becomes sufficient for the gradual surfacing of the model.

For further formalization of the task let us divide the buoyancy force into components: buoyancy force of submerged ice under the sides Q_{IS}, and the buoyancy force of the ice “cushion” under the flat bottom Q_{IB}. We assume at this that the first forces of Q_{IS} along with the main factors generally participate in the periodical process of heeling, while the process of continuous surfacing is determined only by the resultant Q_{IB}. Not taking into account the influence of the buoyancy of submerged ice will not introduce strong distortions in the latter process, but will allow us to simplify the scheme for obtaining the finite calculated dependencies.

In turn, the resulting Q_{IB} does not practically yield the independent heeling moment. As shown by observations, the ice distribution in the transverse section under the bottom at the stage of formation of full value ice basin is close to uniform, due to which the force Q_{IB} will pass near the line of the diametric plane.

Then, in accordance with the proposed description and taking into account the introduced simplifications, the methodology developed for the tank will determine the heeling moment of the model, governed by the sum of action of elastic forces, friction forces and mass forces from the processes of ice pressure, destruction of the floe edges and accumulation of submerged ice. Also there should be determined the buoyancy force of the ice “cushion”, i.e., that part of the ice basin, which is accumulated under the bottom.



(a) (b)

Figure 5. Scheme of forces and moments acting on the model under the conditions of pressures

Thus, it is shown that the change of the model setting at the time of ice pressures occurs under the action of the vertical components of external impacts.

In connection with this, the action of these forces can be replaced by a fictitious procedure of removing-receiving loads, the gravity forces of which correspond to the acting forces, and the gravity centers of loads coincide with the points of application of the resulting forces (Figure 5b). Such approach will allow us by means of the model itself to estimate the external disturbing factors through the equivalent to them forces and moments, not taking into account the differences of the nature of external forces, but investigating their influence on the model stability. The entire process can be presented as a sequence of static positions of the model equilibrium.

Based on the adopted assumptions, the ice heeling moment, which has a complex nature of origin, can be replaced by the equivalent heeling moment M_θ from shifting the fictitious load R_I of variable mass, the gravity center of which is always in the plane of the actual waterline. At this, $R_I = \Sigma Rz^{LB} + \Sigma Rz^{SB}$, where ΣRz^{LB} and ΣRz^{SB} – total impact of forces R_z and Q_{IS} on the model hull from the left and right sides, respectively. The action of the increasing buoyancy force of the ice “cushion” Q_{IB}, unchanged by direction, will be compensated by a gradual removal of “load” Q_I with the gravity center, resting in the main plane.

Using the equation of buoyancy and the metacentric formula of transverse stability (Semenov-Tyan-Shansky, 1960), we will obtain the following expressions, which will make it possible to determine the fictitious masses and the equivalent heeling moment at a random moment of time:

$$\left.\begin{aligned} P_{\Delta D} &= Q_I \pm R_I \\ M_\theta &= D_1 h_1 \sin\theta \end{aligned}\right\}, \tag{2}$$

where $P_{\Delta D}$ – mass of displaced water; $D_1 = D_0 - Q_I \pm R_I$; D_0 – initial displacement; $h_1 = h_0 \pm \Delta h$; h_0 – initial metacentric height; Δh – correction to the metacentric height, caused by the total influence of Q_I and R_I; θ – heeling angle.

A combined action of Q_I and R_I is proportional to the change of the displacement or the lost buoyancy force of the model ΔQ, which can be calculated by formula:

$$\Delta Q = \rho_w g \Delta T \frac{(S_{WL_1} + S_{WL_2})}{2}, \tag{3}$$

or

$$Q_I \pm R_I = \rho_w g \Delta T \overline{S}_{WL}, \tag{4}$$

where ρ_w – water density; g – free fall acceleration; ΔT – average change of the model draft; S_{WL_1} and S_{WL_2} – areas of waterlines between which the displaced volume is located.

The fictitious loads determined according to (4), are differently oriented by height and hence they will differently influence the model stability. Therefore it is important to determine their values independently of each other, similar to how divide the general correction Δh into the components Δh_Q and Δh_R – from the influence of Q_I and R_I respectively.

According to division of disturbing forces introduced above, let us represent the complicated process of external forcing, as a sum of two simple processes. The first process is oscillatory, causing from the action of R_I the periodical change of draft ΔT_R. The second – in the form of the increasing function of draft change ΔT_Q from the constant ice accumulation under the bottom.

Let us determine separately for each of the processes, how the main indicator (measure) of model stability will change – initial metacentric height.

The influence of "load" R_I on stability will be both positive and negative, since the action of the force itself is periodic. The formula for estimating correction Δh_R to the initial metacentric height can be inferred on the basis of the known expressions for estimating the ship stability and setting when receiving or removing the "load" (Semenov-Tyan-Shansky, 1960). In this case the applicate of the gravity center of the received or removed "load" corresponds to the draft at the actual waterline level. The calculated expression for estimating the correction to the initial metacentric height will have the form:

$$\Delta h_R = \frac{\mp R_I}{D_0 \mp R_I}\left(\pm \frac{\Delta T_R}{2} - h_0\right), \tag{5}$$

At consideration of the ice "cushion" influence, the task is solved similar to the task of the ship grounding on the shoal or rocks (Semenov-Tyan-Shansky, 1960). Not dwelling in detail on the theoretical solution, we shall write the finite expression for determining correction Δh_Q to the initial metacentric height, which in this case will always have a negative influence on stability:

$$\Delta h_Q = -\frac{Q_I}{D_0 - Q_I}\left(T - \frac{\Delta T_Q}{2} - h_0\right), \tag{6}$$

where T – draft at the prescribed waterline.

Taking into account the latter, let us write the general calculated expression, allowing us to determine the action of sought for forces:

$$\left.\begin{aligned} M_\theta &= (D_0 - Q_I \pm R_I)(h_0 - \Delta h_Q \pm \Delta h_R)\sin\theta \\ Q_I &= \gamma \Delta T_Q \overline{S}_{WL} \\ R_I &= \gamma \Delta T_R \overline{S}_{WL} \end{aligned}\right\}. \tag{7}$$

In expressions (5), (6) and (7) parameters ΔT_R, ΔT_Q, and θ should be measured at the time of the physical experiment during the entire process of ice pressure. Then we shall consider the practical implementation of this concept in the ice tank with measurement of these parameters.

METHODOLOGY FOR CONDUCTING THE EXPERIMENT

Processing and analysis of the signals of change of the model draft ΔT allowed us to meet the requirement of the theory in terms of division of this parameter into ΔT_R and ΔT_Q. According to the results, a typical received signal can be schematically represented by a plot in Figure 6. As can be seen, curve $\Delta T = f(t)$ depicts a complicated periodic process at the gradual stepwise shift from the initial position with decreasing amplitude of oscillations. The shaded zone on the plot depicts the draft loss due to action of the buoyancy forces of ice accumulated under the hull. Thus, dividing the general process into the components, one can reveal function $\Delta T_R = f(t)$ from the action of cyclic pressure.

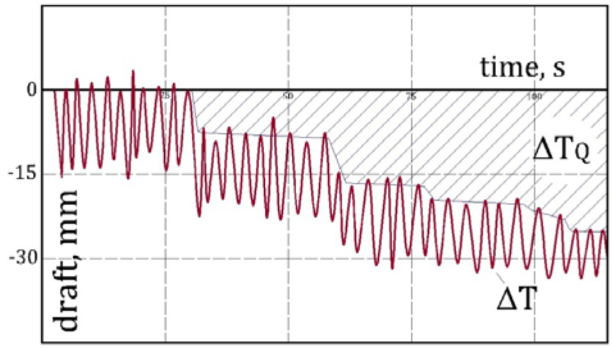


Figure 6 – Typical plot of the draft change from data of the inertial module

The obtained signals at the time $\Delta T_R = f(t)$, $\Delta T_Q = f(t)$и $\theta = f(t)$ are used in the calculated expressions (5), (6) and (7). In the end the result of the experiment is presented by a plot of ice heeling moment in the time function. One determines from the plot the ultimate parameter value which after recalculation to nature can be used in the calculations of stability of the real object taking into account the action of other natural factors (wind, etc.). In addition to the ultimate value, the plot $M_\theta = f(t)$ yields information on the character of the process in general, which is important for prediction of hazardous situations.

The methodology allows us to obtain the change (losses) of the initial metacentric height in time from the influence of the ice "cushion" jammed under the bottom, and also the ultimate value of this loss.

CONCLUSIONS

The work presents the methodology of conducting a model experiment for assessment of the heeling moment of the ice-resistant self-propelled platform of the type "North Pole" under the conditions of ice pressures. Its theoretical provisions and practical implementation in the AARI ice tank are considered. According to the methodology the sought for parameter is determined taking into account the losses of the metacentric height from the influence of the ice "cushion" forming under the bottom of the IRSPP model as a result of cyclic destruction of the overriding ice floe. As an example, some results of a large series of experiments performed with the IRSPP model according to this methodology are given. The latter in perspective can be also used for the real facility, and also for ships and icebreakers that have a significant side tilt with the purpose of creating systems of monitoring for control of stability in real time.

REFERENCES

Kheisin D.Ye, 1962. *Determination of ice loads, acting on the ship hull navigating in ice*. Ph.D.: Leningrad Shipbuilding Institute. (in Russian)

Makarov A.S., Likhomanov V.A., Sokolov V.T., Chernov A.V., Polovinkin V.N., Timofeev O.Ya., Mogutin Yu.I., Simonov Yu.A., 2018. Conceptual principles for creation of the drifting polar research platform. *Arctic: ecology and economy*, 3(31). pp. 65–75. DOI: 10.25283/2223-4594-2018-3-65-75. (in Russian)

Shimansky Yu.A., Poznyak I.I., Kashtelyan V.I., Ryvlin A.Ya., 1958. *Model trials of icebreakers and ice navigation ships*. AARI archives. Leningrad. (in Russian)

Semenov-Tyan-Shansky V.V., 1960 *Ship statics and dynamics. Theory of buoyancy, stability and launching*. Leningrad, Sudpromgiz. 576 p. (in Russian)

Sedov L.I., 1981. *Methods of similarity and dimension in mechanics*. Moscow, Nauka. 447 p. (in Russian)