Technique optimization of holding systems of marine floating objects on the basis of numerical modeling of their behavior

Ilya Teslyaruk, Alexander Bolshev

***Abstract*—**In article, the technique optimization of holding systems of marine floating objects based on execution of serial mathematical experiments simulating the behavior of floating anchored structures under the influence of loads from wind, currents, waves and ices is expounded. Methodology components of mathematical simulation of behavior of floating anchored objects are described, procedures of enhancement of their holding systems, restrictions determined by safety of a construction and optimality criteria of holding systems are given.

***Keywords*—**Mathematical modeling; floating anchored objects; external loads; optimization of holding systems; optimality criterion of the holding system; safety of marine objects

I. Introduction

IN case of design and operation of various floating marine objects, it is necessary to analyze a wide range static and dynamic tasks, studying relocation of these objects under the influence of a wind, waves and currents. Usually for safety of floating object it is necessary to design completely system of its holding and/or to set up its parameters; to specify the level of external influences in case of which safety of object is guaranteed. Thus, being guided by duration of operation of objects, it is necessary to study behavior of constructions under the influence of the most different combinations of external influences [1].

The most universal and rather cheap method of the solution of the specified complex of questions, use of methods of mathematical simulation of behavior of floating constructions for search of options and enhancement of systems of their holding is.

In this operation for the solution of the specified tasks the program package "Anchored Structures" [2] developed at the St. Petersburg Polytechnic University with assistance of the Russian Maritime Register of Shipping is used.

I. E. Teslyaruk is with the Institute of Civil Engineering, Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg, Russia, 195251, e-mail: iteslyaruk@gmail.com

A. S. Bolshev is with the Institute of Civil Engineering, Peter the Great St. Petersburg Polytechnic University, Saint-Petersburg, Russia, 195251, e-mail: bolshev@cef.spbstu.ru

II. Problem Formulation

Design of new holding system of floating marine object, usually, provides a choice of number of anchor lines; caliber of chains or cables of which they consist; lengths of each line or position of an anchor; spatial arrangement of lines; initial tension of lines; type of an anchor and an assessment of its holding ability on this or that ground soil.

At design of holding system of already existing object it is possible to change only the position of anchors, the spatial position of lines and their initial tension.

Optimal new retention system usually is defined by the minimum length and caliber of lines with which it is provided performance of a number of limitations of the external influences guaranteeing safe operation of a construction at any possible combination. [3]

For the already existing object the length, the spatial arrangement and the initial tension of lines in which restrictions on safety of a construction remain in all possible combinations of external influences or in the widest range of influences define the optimality of holding system.

Thus, search of optimal holding system assumes repeated modeling of behavior of floating object under the influence of various combinations of external forces; check of restrictions by criteria of safety of a construction in each of estimated cases; modification of variable parameters of retention system for search of the optimal engineering decision

A. Geometrical modeling of the hull of marine object

Mathematical simulation behavior of floating object begins with creation of three-dimensional geometrical model. In this case the solid-state model is created in the program AutoCAD (Fig. 1). In the same place the surface model of object is created. By means of the special interface of model are transferred to the simulating complex and are used for display of behavior of object in real time in the course of mathematical simulation (Fig. 2) and for calculation of external loadings (Fig. 3).

B. Simulation of external loads on the floating object

The most considerable external loads of buoyant object are connected to impact of disturbance. Within this operation the irregular waves were represented by the range consisting of set of elementary harmonic waves. Thus simulation of a two-dimensional uneasy surface of the sea (a deviation from zero

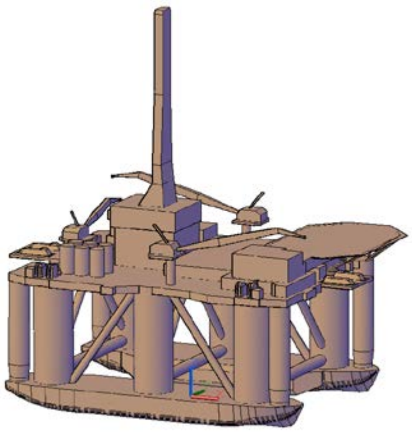

Fig. 1 Three-dimensional geometric model of a floating object in AutoCAD

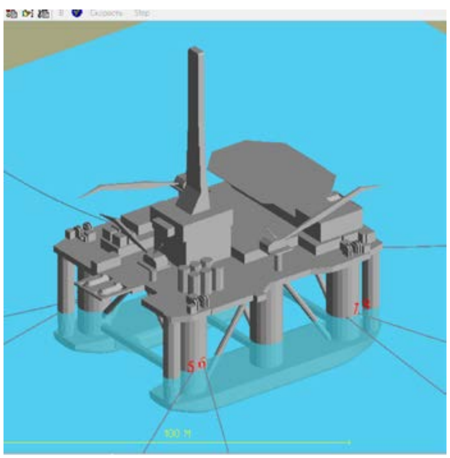

Fig. 2 Three-dimensional geometric model of a floating object in the program «Anchored Structures»

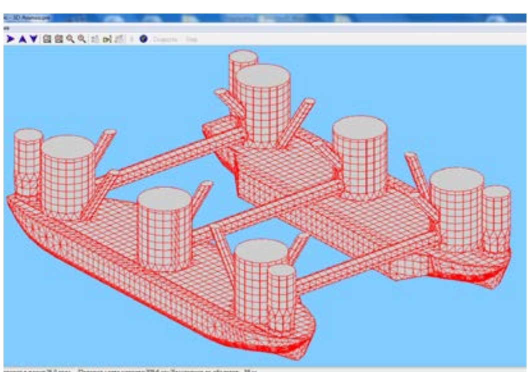

Fig. 3 Surface model of the wetted part of the hull of floating object in the program "Anchored Structures"

level of a quiet surface of $\varsigma(x,t)$ is carried out by means of the following representation :

$$\zeta(x,t) = \sum_{i=1}^{i=n} \alpha_i \cdot \cos(k_i \cdot x - \omega_i \cdot t + \varphi_i) \qquad (1)$$

where $\alpha_i=\sqrt{[2\cdot S(\omega_i)\cdot\Delta\omega_i]}$ – the amplitude of the i^{th} harmonic spectrum; k_i – wave number of the i^{th} harmonic spectrum; ω_i – angular frequency of the i^{th} harmonic spectrum; φ_i – random phase of i^{th} harmonic spectrum uniformly distributed in the range [0, 2π]; $\Delta\omega_i$ – the frequency range of the spectrum $[\omega_i-\Delta\omega_i/2,\omega_i+\Delta\omega_i/2]$, which determines the amplitude of the i^{th} harmonic; x – the horizontal coordinate along the direction of wave propagation; t – time.

The vector of a wave load on a construction in six levels of freedom, depending on the time, was determined by the following formula:

$$F_w(t) = \sum_{i=1}^{N}\sum_{n=1}^{M} F_{in}(\omega_i,\theta_n)\cdot\sin(\omega_i\cdot t+\varphi_{in}) \qquad (2)$$

where $F_{in}(\omega_i,\theta_n)$ – vector of amplitudes of loading from i^{th} harmonic spectrum of excitement propagating in the direction of the n^{th}; t – time; ω_i – the angular frequency; φ_{in} – phase of in^{th} harmonic spectrum of the load; N, M – the number of partitions of the three-dimensional spectral intervals.

For receiving wave loads and hydrodynamic characteristics of constructions in a program complex the variety of widely known method of hydrodynamic features – a method of spatial sources of radiation – is used [4]. This method is based on obtaining the filling and reflected potentials of disturbance and integration of resultant liquid pressures on the wetted surface of a construction.

In case of calculation of ice loads on floating objects it is, usually, necessary to make calculations for conditions of their interaction with fields of equal or hummocky ice (Fig. 4,5,6). Sometimes the assessment of consequences of interaction of floating object with icebergs or their fragments is required (Fig.7). Methodologically the calculation of ice loadings can be done in quasistatic or dynamic statement.

It is necessary to emphasize that interaction of ice with floating anchored objects is quite often characterized by dynamic processes of ice cutting by structure. Unfortunately, the studying of the dynamics of this interaction even with a fixed structure, still has not found the proper development in the world. Questions of dynamic interaction of ice with a pliable construction are even less studied. In this regard in a

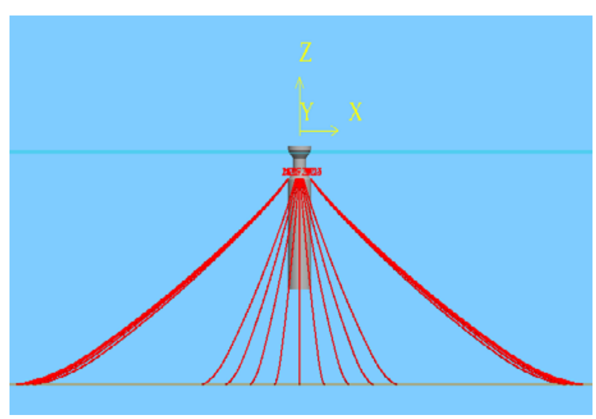

Fig. 4 Ice-resistant option of a SPAR platform

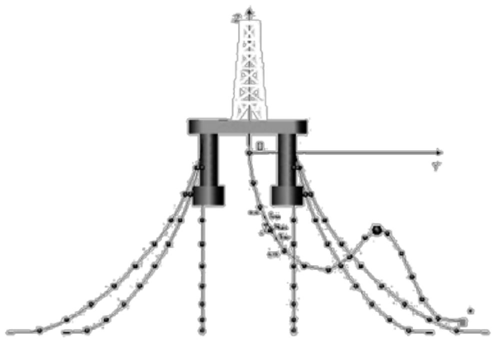

Fig. 8 Simulation of dynamics of floating object together with dynamics of lines

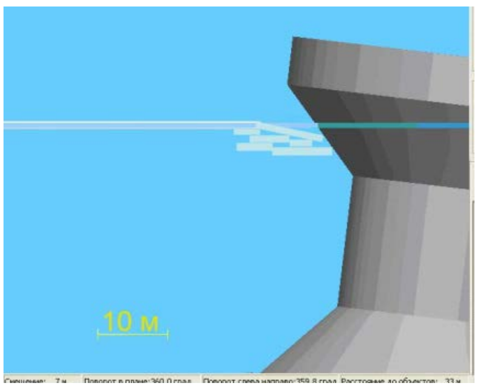

Fig. 6 Modeling of interaction of the ice-resistant TLP platform with a field of equal ice

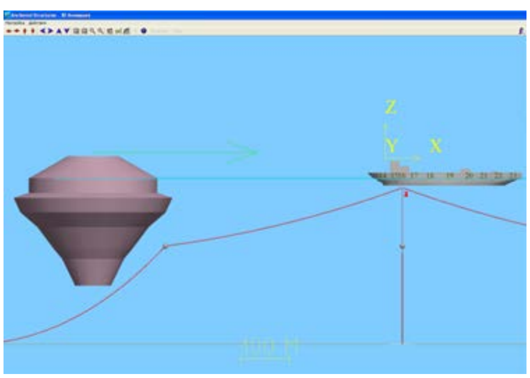

Fig. 7 Modeling of interaction of the vessel FPU with an iceberg

software package own approach to modeling of dynamic interaction of ices with inclined barriers is realized [5]. Ice formations are generally presented as consolidated part and hummock keel, from which the loads are calculated independently from each other. The movement of the ice formation is described by specifying of its direction and moving speed, and movement of a pliable construction is defined as a result of integration of its equations of the movement taking into account contact forces. Loadings from keel of a hummock are calculated due to dependences recommended by international standards, and for calculation of forces from smooth ice or the consolidated part of a hummock the author's technique is used [6].

In case of calculation of forces and the moments from a wind the problem definition assuming existence of prior data about the sail area and resistance when blowing a construction under different angles was used.

In this case the wind load on a construction is calculated by a formula:

$$F = \rho_a \cdot \overline{V_w^2} \cdot C_w \cdot A_w \cdot (\alpha_w - x_b)/2 \tag{3}$$

where V_w – the estimated average wind speed, m/s; ρ_a – density of air; $A_w(\alpha)$ – function of the sail area from an angle of the direction of a wind concerning a construction ; C_w – resistance coefficient; x_b – construction turning angle in the plan.

In case of the account dynamic component of wind speed was presented in the form:

$$V_w = \overline{V_w} + V_w' \tag{4}$$

The dynamic component of the wind speed spectrum is described by wind gusts according to regulatory documents ISO1901-1 [7].

Calculation of forces and the moments from a current assumes existence of prior data about the area of underwater windage of object and resistance in case of a construction flow under different angles. Determination of forces of a current was executed on estimated formulas similar (3).

C. Simulation of holding system

The modelled anchor lines can represent different types of rope, circuits, flexible connections of pipes or any their combinations. Safety of operation of floating structures essentially depends on the reliability and longevity of the used holding system [8].

Calculation of stresses in anchor lines was made by a quasistatic method, with small depths of the sea [9], thus the tension and a path of the line were function of provision of a hawse point of a construction. In case of calculation of anchor lines their stretching and possibility of laying down of part of line on a water area bottom which, in turn, can have an inclination were considered.

In case of big to sea depths response of anchor lines was calculated by a dynamic method (taking into account dynamics of lines). In this setting, the lines were considered as elastic, heavy, flexible threads the weight of which concentrates in nodal points [10]. Thus, each line was described as a daisy of elementary masses connected by elastic weightless threads.

D. Solution of static and dynamic problems

In case of simulation of tasks of a statics the decision of system of six non-linear algebraic equations representing [11] a balance of all the forces acting on structure was made:

$$C(X_c)+F_R(X_C,L_1)+F_S(X_C)+F_B(X_C)+F_{df}+F_w+F_c+F_i=0 \tag{5}$$

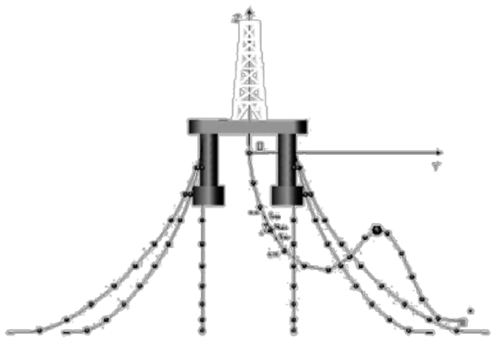

Fig. 8 Simulation of dynamics of floating object together with dynamics of lines

where F_{df}, F_w, F_c, F_i - external static forces of wave drift from a wind, a current and ice respectively; X_c - the displacement vector of a construction in six levels of freedom; $C(X_c)$ - vector of restoring forces; $F_R(X_c,L_1)$ - vector of the forces of reaction system of anchoring; $F_S(X_c)$ - vector of reaction of mooring lines; $F_B(X_c)$ - vector of reaction of fenders.

The dynamic problem was solved in a time domain by means of integration of system of ordinary non-linear differential equations of movement of anchored floating object [2].

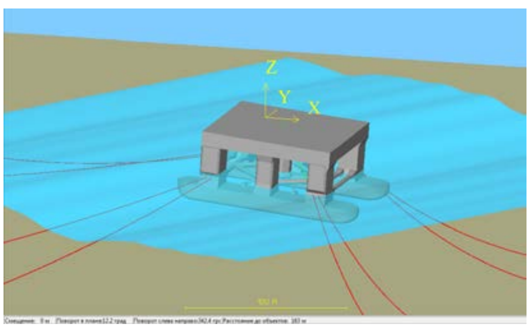

Fig. 9 Simulation of pitching of floating object in a 100-year storm repetition

E. Restrictions on behavior of floating object

Safety of operation of the floating object is usually determined by performing the following restrictions: the maximum permissible vertical and horizontal movement; the maximum permissible angles of heel and trim; minimum permissible reserves of tension in the anchor links; minimum permissible reserves the horizontal load transferred to the anchor.

$$\begin{cases} \Delta X < \Delta X_{\max} \\ \Delta Y < \Delta Y_{\max} \\ \Delta Z < \Delta Z_{\max} \\ \varphi_x < \varphi_{x\max} \\ \varphi_y < \varphi_{y\max} \\ \max_i(F_i) < F_{\max} \\ \max_i(f_{xi}) < f_{x\max} \end{cases} \tag{6}$$

where ΔX, ΔY, ΔZ - shift of a barycenter of floating object along horizontal and vertical axis under the influence of static and dynamic loads; ΔX_{max}, ΔY_{max}, ΔZ_{max} - the most admissible shifts of object ; φ_x, φ_y - angles of heel and trim under the influence of external forces; φ_{xmax}, φ_{ymax} - the most admissible angles of heel and trim; F_i - the maximal tension of anchor line number "i" during pitching of the object under the influence of loads; f_{xi} - the maximal horizontal effort transferred to an anchor with number "i"; F_{max}, f_{xmax} - the most admissible tension of anchor line and the holding anchor force.

The listed restrictions, as a rule, are specified for the construction survival modes during an extremal storm [12], for the modes of operation or for execution of specific sea operations and depend on the accepted calculation method (quasistatic or dynamic).

F. Plan of numerical experiment and criteria of an optimality

For execution of numerical experiment at first the initial matrix of estimated cases enveloping possible combinations of levels of external influences from a wind, disturbances and currents taking into account a variation of propagation directions of a wind and disturbance in the range from 0 to 360 ° was formed.

Further, for some initial values of parameters of holding systems modeling of the entire matrix of the estimated cases was executed, execution of restrictions on safe criterions was analyzed and critical combinations of external influences in case of which the situation appeared the worst. The values of the maximum displacement of the floating objects or coefficients of margin of safety of anchor lines in case of a critical combination of external influences were associated with the selected earlier variable parameter values of holding systems.

Further, modification of parameters of holding systems was executed and the cycles of simulation were repeated until it was possible to provide execution of all safe criterions in case of all possible combinations of external influences.

III. Conclusions

Use of methods of mathematical modeling and application of high-settlement complex allow to formalize the task of finding the best parameters of holding systems of floating anchored objects by busting combinations of external influences, simulation of behavior of object in case of implementation of each combination, assessment of safety of object in each estimated case and coherent modification of the parameters of holding systems to ensure safe operation of the floating object at all possible levels of external load.

In the simplest case, when optimization only of an initial tension of anchor lines was carried out, the initial matrix of calculated cases (k=1,2 … M) extended due to introduction of a column of the varied parameters - the ranged sequence of initial tension (j=1,2 … N). In this case, total number of calculated situations was defined by multiplication of number of estimated cases in an initial matrix on number of ranks of an initial tension of lines (MxN).

As optimality criterion the following minimax criterion which was implemented in case of unconditional execution of restrictions (6) was accepted:

$$\max_j \left(\min_k \left[\frac{F_{\max}}{\max_i \left(F_{i,j,k} \right)} \right] \right) \quad (7)$$

Thus, options of an initial tension (j) the level of a tension in case of which in the worst combination of external influences (k) the greatest margin of safety of the most loaded line (i) was provided was considered as the best.

With increasing number of optimized parameters (caliber of lines, length of lines, plan layout of lines, etc.) the ranged sequence of these parameters expanded a column of the varied parameters (j=1,2 … N1), and the schematic diagram of optimization remained invariable. Of course, the increase in number of variable parameters is rapidly increased the volume of mathematical simulation. By using of the software package stated above this volume was restricted to ten thousand estimated cases.

References

[1] Shkhinek K., Karna N.,Lehmus E.,Gudmestad O.T., Strass P., Loset S., Mischenko S., A. Bolshev, Chasovskih E. Potential structures for the Russian arctic offshore, Proc. Of 16th Int.Conf. OMAE'97 and 14th Int.Conf. POAC'97, Vol.IV Arctic/Polar Technology p.183-190.

[2] A.S. Bolshev, M. A. Kuteynikov, S. A. Frolov Mathematical simulation of sea buoyant objects in the program complex "Anchored Structures", The scientific and technical collection of RMRS, release 36, 2013, p. 68-90

[3] A.S. Bolshev, E. Toropov, O .Gladkov,, A. Gintovt, D .Mirzoev, S. Frolov Effect of the Selection of Mooring System on Characteristics of Platforms in Wave and Ice Conditions, Proc.of Eleventh (2001) International Offshore and Polar Engineering Conference, Vol.II, page 295-306, Stavanger, Norway, 2001.

[4] Garrison C.J. and P.Y. Chow Wave forces on submerged bodies, Journal of the Waterways, Harbors and Coastal Engineering Division, vol. 98, No. WW3, pp. 375-392, American Society of Civil Engineers, New York, USA.1

[5] Bolshev, K. Shkhinek, S. Frolov Mathematical modeling of floating anchored objects behaviour under the level ice of ridges influence, Society of Petroleum Engineers - Arctic and Extreme Environments Conference and Exhibition 2011,Vol. 2, p. 934-945.

[6] A.S. Bolshev, K.N. Shkhinek, S.A. Frolov Mathematical Modelling of Floating Anchored Objects Behavior under Ice Influence, Proceedings of the Tenth (2012) ISOPE Pacific/Asia Offshore Mechanics Symposium, Vladivostok, Russia, 2012, p.68-72.

[7] ISO 19901-1 Petroleum and natural gas industries Specific requirements for offshore structures Part 1: Metocean design and operating considerations, 2005.

[8] A.S. Bolshev, O. A Grigoryeva, S. A. Frolov, O. T. Gudmestad Assessment of Deflected Mode and Lifetime of Anchor Lines and Risers. Proceedings of the Twenty-second (2012) International Offshore and Polar Engineering Conference, 2012, Vol.2, p.275-280.

[9] S. A. Frolov Statics and dynamics of the buoyant constructions fixed by floppy elastic lines// the Paper of the thesis on competition of an academic degree of Candidate of Technical Sciences, SPb, SPbSTU, 1992 , p. 16.

[10] Bolshev A.S. Statics and dynamics of anchored floating structures with non-linear characteristics of anchored system Monograph, Gdansk, 1993, 218 p.

[11] Bolshev A.S., S. A. Frolov Application of vectorial piecewise linear operators in non-linear tasks of a statics and dynamics of anchored structures // Construction mechanics and calculation of constructions, Collection of scientific works of SPbSTU, SPb, 1992, p.137-144.

[12] Rules of classification, construction and the equipment of buoyant drilling rigs and sea stationary platforms, RMRS, SPb, 2014, p. 479