Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 629.563.2:004.942:626/627

DOI: 10.34910/MCE.111.12

Mooring system optimization for marine floating hydrotechnical structures

A. Bolshev , ***S.A. Frolov*** , ***E.V. Shonina*** ✉

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ *shonina_ev@spbstu.ru*

Keywords: offshore structure, mooring system, multi-objective optimization, penalty function method, optimization, semi-submersible platform, mooring, tension force, method of golden section

Abstract. Existing offshore areas require development and mining using floating structures. The article presents design issues and settings of anchor mooring systems for marine floating structures. Improving and optimization methods for mooring systems, presented in publications of Russian and foreign authors, are discussed. The parameters influencing the safety of floating marine structures operation are identified. The parameters that are advisable to take as criteria are discussed. The restrictions imposed on non-criteria parameters are considered. The optimization criterion of the marine floating structures mooring systems in extreme operating modes is formulated. An optimization method for mooring systems is suggested in accordance with the proposed criterion. The study gives an example of mooring system optimization in the storm mode for a platform operated in ice-free seas. A similar methodology can be used for mobile ice-resistant platforms, conceptual variants of which are being developed for operation in Arctic conditions. Research results were obtained by the method of mathematical modeling.

1. *Introduction*

The development tasks of the global ocean resources lead to the need of the construction and operation of various structures that have been functioning for a long time in offshore waters. Many of these structures have ability to move in offshore waters and positioning in the targeted water area using an anchor mooring system. Such floating objects include semisubmersible drilling platforms, floating cranes, floating berths, floating power structures, offshore pipelay vessels, submerged floating tunnels, etc. [1].

Operation of offshore structures is always associated with the risk of serious accidents due to extreme environmental loads. Often such structures operate in offshore waters, where the impact of wind loads and extreme storm waves can lead to irreversible effects. High cost of structures, their isolated location from coastal bases and the availability of operating personnel constantly working at these structures determines highest requirements for reliability and structure safety.

One of the most important factor determining safety of the considered floating structures is mooring system failure-free operation. It must ensure the upholding of all restrictions due to the continuation of normal operation or survival preservation of the marine structure under any environmental loads [2, 3].

At the design phase of an offshore floating structures or at the design phase of positioning it in offshore waters, it is always necessary to solve the issues of the composition and configuration of its mooring system, the azimuthal orientation of the floating anchored structure, the selection of the lengths and tension of mooring lines, influence of mooring angle, etc. This task leads to different solutions

Bolshev, A., Frolov, S.A., Shonina, E.V. Mooring system optimization for marine floating hydrotechnical structures. Magazine of Civil Engineering. 2022. 111(3). Article No. 11112. DOI: 10.34910/MCE.111.12

depending on the floating structure characteristics, the intensity of the expected environmental loads, the depth of the marine waters, etc.

Searching for the best decision for the mooring system parameters presume the ensure of the highest level of the structure safety within the prescribed operating conditions.

1.1. Problems of mooring systems design and floating structures positioning

The problems that appear at the design stage of the mooring system for the floating structure are associated with the uncertainty of the environmental conditions for its practical use. The offshore floating mooring structures are mobile. In prospect they can be used in different seas, at different depths, in water areas where the parameter of wind-wave conditions differs very significantly. Designing of a newly created mooring system requires parametrization: number of lines of the mooring system, their maximum length, caliber of the chains or cables of these lines, location of the hawser hole on the structural body, linear weight and elasticity-strength characteristics of the elements of the mooring line, mooring line type, mass and the holding force of the anchors.

Selection of parameters usually depends on the maximum permissible values of wind velocity, height and wave period, sea depth due to the uncertainty of the environmental conditions in the water area of the structure position. This ensures the safety of structure positioning during usage of the mooring systems. In any case the process of creating a mooring system is associated with ranging the values of numerous parameters and searching for such combinations of these parameters at which the structure is capable of safely functioning under extreme environmental loads.

The problems that appear at the stage of structure positioning in certain water area look more precise. In this case the external conditions, the number and configuration of the mooring lines, their elastic-weight characteristics, the parameters of the floating structure anchors are already known. It is necessary to determine the best orientation of the structure, mooring lines layouts, their length and tension to ensure the unconditional safety of the structure during the period of extreme storms expected in a certain water area. It is also necessary to find the best combination of the listed characteristics that ensure the highest safety level of the structure's functioning under the worst external conditions.

Commonly it is possible to change the tension of the lines of the structure with an already deployed mooring system during its operation. This ensures that the conditions for the operability of the structure are met. In this mode it is necessary to select the tension of the lines to fulfill the constraints of the structure's operability (more severe than in the storm mode) or to select the extreme external conditions under which the operation of the structure is permissible.

The problem of optimization of the mooring systems for keeping floating anchored structures in a storm (survival) mode is considered in this article. This task is wider in comparison with the task of optimization in operation mode. At the same time, this task is one of the main elements of the optimization of the mooring systems at the stage of its initial design.

1.2. Mooring systems design experience

The experience of designing mooring systems and methods for determining the parameters of these systems are presented in a number of Russian and foreign publications.

In particular, the regulatory document of the Russian Maritime Register of Shipping ND 2-020201-015 “Rules for the classification, construction and equipment of mobile offshore drilling units and fixed offshore platforms” for floating drilling units contains recommendations on the choice of mooring lines for use at the stage of driving the platforms to the positioning point: estimating the length of mooring lines method, their caliber and mass of anchors based on the given displacement of floating structures and its surface exposed to the wind. This method is very approximate, applicable for a limited range of wave and wind velocity. It does not take into account the mooring lines position, so its application to the analysis of the platform mooring system in operation or storm modes is problematic. In the same regulatory document, it is proposed to study behavior of the mooring systems in various modes of operation to select their parameters, to determine the extreme forces in the elements of the mooring system, to compare them with safety criteria and, on this basis, to improve the configuration of the mooring system. However, the organization procedure for improving the parameters of the mooring system, parameter determination procedure of this system is not stated in the regulatory document.

Nevertheless, the engineering practice of Russian design organizations in the design of the offshore anchored structures complies with the provisions of the regulatory document of the Register of Shipping. For example, in [4], the authors show the mooring system design, performed using the “POSITION” software package in accordance with ND 2-020201-015 “Rules for the classification, construction and equipment of mobile offshore drilling units and fixed offshore platforms”. The results of the work make it possible to determine the main parameters of the mooring system and to make a conclusion that the mooring system provides a reliable position of the platform with a permissible displacement.

The influence of various loads on the movement of a floating structure and on the mooring system was studied in [5]. The authors also consider the horizontal stiffness of the system as the main parameter characterizing the operational safety. But during the preliminary design of the mooring system the following safety criterion is taken into account: the maximum tension of the mooring line should not exceed the allowed values. Dynamic analysis for three different depths was performed in time domain using Simo-Riflex-AeroDyn software packages.

Similar criteria are discussed in article [6]. The authors presented the results of the mooring analysis of semisubmersible platform Scarabeo 7 according to the rules of two classification societies: American Petroleum Institute (API) and Det Norske Veritas (DNV). The aim of the study was to compare the obtained results. During positioning of an offshore object the main criteria must be observed. The authors also include maximum displacement of the object limited to avoid damage or breaking of riser and the maximum tension in lines, determined by the safety factor.

The requirements for the safety factor as a criterion for assessing the positioning system are also considered by the authors in [7]. Safety factors represent the ratio of breaking load to maximum force in the most loaded mooring line. Numerical modeling was carried out in software package “Anchored Structures”. The calculation analysis had given a high convergence of the results with real processes.

Similarly, the requirements of the “Rules for the classification, construction and equipment of mobile offshore drilling units and fixed offshore platforms” are taken as the main criteria for determining the parameters of mooring lines in article [8]. The authors performed a series of preliminary calculations to determine the effective length of the mooring line and chose the length of the line at which the vertical force transmitted to the anchor equals zero. Mooring parameters were assessed using the POSITION and “Anchored Structures” software packages.

The study of a floating structure movement and the selection of a suitable mooring system are discussed in [9, 10]. Seven symmetrical mooring systems were modeled, consisting of four or eight mooring lines to find the best mooring system. The results of the analysis show that the optimal mooring system is a variant with eight lines and 60° angle between two adjacent lines (the criterion for comparison is the smallest horizontal displacements). Second variant is the one with eight lines and 30° angle between two adjacent lines (the criterion is the lowest tension values).

The authors of the listed articles perform the design and analysis of the mooring systems operation, choosing various parameters of the system as an evaluation criterion. Mainly mooring systems selected for the calculation are not further optimized because they are sufficient for the normal operation of the structure. Due to the high computational efforts associated with modeling of the mooring systems, optimization algorithms are not used in the design cycle. Without the use of formal optimization approaches the design of mooring systems is limited to an iterative engineering and design approach based on experience and search for an acceptable engineering solution.

In a number of foreign articles, the authors approach the issue of optimization in more detail using heuristic methods [11–15]. One such method is the genetic algorithm. A genetic algorithm is a type of evolutionary computation that solves optimization problems using natural evolution methods. The algorithm is an incomplete enumeration of mooring systems variants, which improves the value of the objective function. For example, in [16] the goal of optimization is to minimize the displacement of the structure. The minimum value of the objective function is calculated using an iterative genetic algorithm. The result is optimized anchor positions. In this case the set of environmental conditions (waves, winds loads and sea currents) is converted into equivalent external static force acting on the floating structure. Dynamic analysis of the floating structure behavior is not used in the calculation of mooring systems.

The genetic algorithm is used in the article [17], which describes the procedure of developing the code aimed at solving the problems of optimization of the mooring pattern. The author defines the optimal mooring system as the one that minimizes the constraint force of the floating structure (platform) itself. In this case, the author, in addition to the displacement of the structure, takes into account the following aspects affecting the choice of the optimal system: angle of the structure position, the platform mooring system, distribution of external loads; the length and tension of each line for selection of materials and sizes. The objective function which takes into account the displacement of the structure, is calculated in the MIMOSA software package, while the genetic algorithm is executed using the MatLab language. The genetic algorithm is also successfully applied in works [18–20].

Adequate results of the optimization process can be shown by the particle swarm method. It considers calculating a large number of mooring system variations to create a point cloud, within which it is possible to search for the best value of the objective function. This approach is used to solve the problem of floating platforms positions in [21, 22]. In [21] modeling was carried out for deep-water systems in the PROSIM software for the operating mode, taking into account the maximum allowable offset of the structure in order to avoid riser breakdown, as well as taking into account the safety factor. This algorithm has already been successfully used by the authors for another OtimRiser software package in [23].

A review of existing works by Russian authors suggests that most of the modeling and calculation methods allow calculating pre-selected mooring lines, but the issue of choosing the optimal position system and its adjustment is not solved. Because of this an engineer has to select a mooring system based on design experience, model and calculate its parameters. Then it's necessary to iteratively improve the parameters to values satisfying the safety criteria.

As for foreign studies, works with the use of fuzzy logic are presented on the issue of optimization of mooring systems. The approaches make it possible to form a fuzzy set, and the optimization problem implies the choice of the «middle» variant that satisfies the given constraints. The result is not an optimal solution, but a close to optimal one. In addition, in the considered solutions modeling the behavior of an anchored structure and the operation of its mooring system are considered separately from the optimization procedure. Processes are executed in different software environments. This approach excludes the possibility of obtaining an exact optimal solution.

It is therefore possible to conclude that the development of methods that allow obtaining an accurate optimal solution for the parameters of the mooring system for marine floating anchored structures is a logical completion of the ideology of Russian regulatory documents (for example, ND 2-020201-015 "Rules for the classification, construction and equipment of mobile offshore drilling units and fixed offshore platforms"), develops methods for finding optimal solutions based on planning numerical experiments [24, 25] and allows to abandon approximate solutions of fuzzy logic in a number of practical problems.

1.3. Problem definition

In the scope of this article the following tasks are set:

- Identify the parameters affecting the floating structure safety in general and mooring system in particular.
- Determine a parameter that can be accepted as a criterion value.
- Identify constraints in the design of mooring systems.
- Formulate an optimality criterion for the survival mode.
- Develop a method for optimization of the mooring system of a floating anchored structure in survival mode.

There are a number of parameters characterizing the behavior of an anchored structure under the influence of static and dynamic environmental loads, which affect its safety:

1. The mooring lines tension, which must not exceed the ultimate breaking load at any time.

2. Horizontal displacement of the structure, which must not lead to damage to its structural elements.

3. Vertical displacement of the structure, which must not lead to the climb of waves on the deck of the structure.

4. Angular displacement of the structure, which must not obstruct the functioning of the structure and the crew life.

5. Lack of the anchors movement, which guarantees the preservation of the initial characteristics of the structure mooring system.

To solve the optimization problem, it is necessary to determine which of the listed parameters have the greatest impact on the behavior and operation of the entire structure. To do this it is necessary to take into account the consequences to which they can lead:

1. Lines break can certainly lead to emergency situations.

2. Horizontal movements during operation mode can lead to riser break. This could be the cause of the oil spill. However, the risers are usually detached in survival mode (extreme storm) and this parameter becomes insignificant.

3. Vertical movements of the structure, which can lead to the climb of waves on the deck, are an undesirable event. But it does not necessarily lead to emergency consequences.

4. Large angular displacements of the structure are usually undesirable, but do not lead to emergency consequences.

5. Due to the anchors movements, the floating structure may have displaced and the properties of the mooring system may change. Movements of anchors are usually not allowed in the operating mode of an anchored structure. However, in survival mode, when there are no restrictions on the linear movement of the structure, the movement of the anchors will not lead to an accident. After the storm is over, the mooring lines tension and the settings of the mooring system can be reset.

Thus, the lines tension can be taken as the criterion that mostly determines the safety of a floating structure. The remaining parameters can be considered as constraints that will be taken into account during mooring system optimization according to the selected criterion.

2. Methods

2.1. Formulating of the criterion for the mooring system optimization in survival mode

Floating structure must be positioned in the water area and must be held by an anchor mooring system in survival mode. In this case, the orientation of the structure, which is characterized by the azimuth angle β, is the subject of research in the optimization process.

The mooring lines of the floating structure have a known maximum possible length, and their elastic-weight characteristics are presented in the technical passport. The length of the lines can be calculated during the optimization process and it is limited by the following formula:

$$H \le L \le L_{max}, \tag{1}$$

where L is the line length used in the mooring system, H is the sea depth, L_{max} is the maximum possible line length.

The number of mooring lines N is known; the inclination angles are selected during the optimization process.

The initial lines tension including the margin of safety should not exceed the breaking force. This safety factor is determined by ND 2-020201-015 and depends on the selection mode (survival, operation, emergency mode), as well as on the method of analyzing the behavior of the structure (quasi-static or dynamic). Thus, the formal constraint on the initial tension is:

$$0 < F_0 < F_b / k_n, \tag{2}$$

where k_n is the standard safety factor for the mooring lines tension, F_b is the breaking force of the mooring lines, F_0 is the initial tension of the mooring lines.

Commonly a floating anchored structure which is positioned in the offshore waters is exposed to wind, currents and waves. These external loads are time-dependent and can impact in different combinations and from different directions. Usually, combinations of loads are taken during the analysis of extreme impacts. These loads combinations are typical for each force direction taking into account the wind rose, currents and waves. In prospect, the force direction will be designated by the index k (for example, $k = 1,\ 2 \ldots 8$).

Formalizing the idea of the greatest safety of a structure from the point of view of the tension margin, the best variant will be: such a variant of the mooring system when the most tension margin in the most tensioned anchor line is retained (on the worst combination of external loads (the worst load direction) in extreme storm). The mathematical formulating of this criterion is presented below:

$$\max_{F_0, L_i, \beta, \alpha_i} \min_{k} \left[\frac{F_b}{\max\limits_{i} F_{i,k}\left(F_0, L_i, \beta, \alpha_i\right)} \right], \tag{3}$$

where F_0 is the initial tension of the mooring lines, L_i is the length of the line with the number $i\left(i = 1,\ 2, \ldots n\right)$, α_i is the plan inclination angle of the line, β is the azimuth angle of the structure.

The proposed criterion assumes that certain parameters of the lines are defined. The line tension and the azimuth angle of the structure are known, line length and the plan inclination angle of the line are defined. Further, the behavior of the structure under storms from different directions (k) should be modeled. The maximum tension $\left(\max_i F_{i,k}\left(F_0, L, \beta, \alpha\right)\right)$ calculated in any line is determined for each direction. The safety factor for this “worst” line is calculated. The safety factor for the “worst” line under the external loads from the “worst” direction $\left(\min_k\right)$ is determined as the result of such numerical experiment. Then, changing the parameters F_0, L, β, α it is necessary to find such combinations for which the “worst” safety factor will be the maximum possible.

2.2. Solution procedure

Mathematically the task solution is minimizing the functional J subject to series of restrictions:

$$\begin{cases} J\left(F_0, L_i, \beta, \alpha_i\right) = \max\limits_{F_0, L_i, \beta, \alpha_i} \min\limits_{k} \left[\dfrac{F_b}{\max\limits_i F_{i,k}\left(F_0, L_i, \beta, \alpha_i\right)} \right] \\ \min\limits_k \Delta_k > \Delta_0 \\ \max\limits_k \varphi_{x,k} < \varphi_{xmax} \\ \max\limits_k \varphi_{y,k} < \varphi_{ymax} \\ \max\limits_i F_{i,k} < \dfrac{F_b}{k_n} \\ L_{min} < L_i \le L_{max} \\ \alpha_{i-1} < \alpha_i \le \alpha_{imax} \end{cases}, \qquad (4)$$

where Δ_0 и Δ_k are the minimum permissible clearance of the floating structure and the minimum clearance recorded during modeling an extreme storm from the “ k ” direction; $\varphi_{x,k}$ and φ_{xmax} are the maximum angle of roll of the structure during modeling an extreme storm from the “ k ” direction and the maximum permissible angle of roll; $\varphi_{y,k}$ and φ_{ymax} are the maximum trim angle of the structure during modeling an extreme storm from the “ k ” direction and the maximum permissible trim angle; $F_{i,k}$ is maximum line tension with number i under the impact of a storm from the “ k ” direction.

The initial values of the optimized parameters are determined as follows. The initial tension of all mooring lines is equal in value within the limits (2). The tension of all lines changes during implementing the optimization procedure, but it also remains equal in all lines to ensure a symmetric constraint force from the multidirectional loads.

The azimuth angle of the structure varies within $\left(0, \pi\right)$ in the process of optimization because of the symmetrical form of floating structures about the direct axis. The initial angle value is arbitrary within the definition limits.

The plan inclination angles of the lines are set and changed for each line with the number i $\left(i = 1,\ 2, \ldots n\right)$. To start the optimization process, the initial values of the lines plan inclination angles α_i can be presented as follows: $\alpha_1 = \alpha_0,\ \alpha_i + 1 = \alpha_i + 2\pi/N$, where α_0 is an arbitrarily assigned angle, index i determines the number of the line, N is the number of mooring lines. To keep the symmetric constraint reactions of the mooring system, the plan inclination angles of the lines that are in the first quadrant are considered as independent. The remaining plan inclination angles are determined by symmetry about the X-axis and Y-axis. The initial values of independent angles are set in the range $\left(0, \pi/2\right)$ so that the plan inclination angle of every next line will be greater than the previous one.

The initial line lengths are set the equal based on constraint (1). The lengths of the lines located in the first quadrant are considered as independent to ensure the equal constraint force in mooring lines under the multidirectional loads during further optimization. The remaining lengths are taken equal to them by symmetry about X-axis and Y-axis.

Thus, to solve the problem it is necessary to perform a multiparameter optimization of functional (4) with known initial values of the variables and with a number of constraints.

First, it is necessary to discuss the nature of the functional J. The functional must be convex, continuously differentiable and must have continuous first and second derivatives to apply most of the methods for finding an extremum. Unfortunately, this functional is specified implicitly and it cannot be investigated formally (analytically) from the point of view of the indicated requirements. However, from physical considerations, it can be assumed that it is convex. The formal accounting of existing constraints written in the form of inequalities is a separate issue. Unfortunately, these constraints also have no analytical form and specified implicitly. In this regard, it is difficult to use, for example, gradient methods with a gradient projection onto the constraint zone [26], because the zone of constraints is unknown in advance and it is update during the research.

In prospect it is proposed to form a functional that would include all constraints by using the penalty function [26] taking into account the features of the functional and constraints (4):

$$J_f\left(F_0, L_i, \beta, \alpha_i\right) = \max_{\alpha_i,\beta,L_i,F_0} \min_k \left[\frac{F_b}{\max\limits_i F_{i,k}\left(F_0, L_i, \beta, \alpha_i\right)} \right] - \sum S_q, \tag{5}$$

where S_q is the penalty function generated for each constraint from (4).

In functional (5) compared to (4) all constraints are presented in the form of penalty functions S_q,. Each of them is responsible for the penalty for constraint violation with number q. If all constraints are met, we will get the same functional (4).

The penalty function for an arbitrary parameter $x\left(a < x < b\right)$ is proposed to be entered by following formulas:

$$S = p\frac{a - x + \left|a - x\right|}{a},$$
$$S = p\frac{x - b + \left|x - b\right|}{b}. \tag{6}$$

The penalty function in the form (6) takes zero value in the zone where the constraint is fulfilled. It has a positive numerical value in the zone where the constraint is violated. The p factor is used to scale the penalty function.

To find the extremum of the functional (5), the method of sequential optimization of the functional with respect to each of the arguments is used. In this case, optimization (5) for the parameters F_0, β, α_i, L_i is sequentially carried out until the value of the objective function stabilizes in the zone of the extreme value. The problem is deemed to be solved if the extremal value of functional (5) is found, and the formula $\sum S_q = 0$ is satisfied.

The procedure is implemented for one current variable F_0, β, α_i or L_i at each step of the coordinatewise optimization. For optimization (5), the method of dividing the interval is used. At the first step of the optimization procedure the initial interval is divided into three parts by two new control points insertion. Then the values of the functional at these new points are calculated. And then, for further research, the interval is left where the control point with the extreme value of the functional is located. The procedure is repeated cyclically. The interval where the extremum is located is reduced at each step. The procedure stops when the size of the uncertainty interval becomes comparable to the permissible error.

There are three similar approaches that implement this idea. These are the half-interval method, the Fibonacci method and the golden section search method [26]. All of them differ only in the way the interval is divided into parts. The errors of these methods are comparable, but the golden section method and Fibonacci method have a noticeable advantage. This is due to the special method of dividing the interval, when one of the two control points that divide the interval is used in the next iteration. In this research the golden section method has found practical application. It requires “M” numerical experiments $\left(M = -4.82\ \log \varepsilon\right)$ (relative result error ε of the extremum search).The “M” value in practical tasks was within limits of 10 ones.

3. Results and Discussion

The stated methodology was implemented in software package [27], which allows modeling in the time domain the behavior of offshore floating anchored structures under the loads of wind, current, waves and ice. The software implementation of the methodology and the capabilities of the software package made it possible to perform parallel modeling of the behavior of anchored structure on a personal computer while simultaneously solving eight problems in the time domain associated with the storm loads from different directions. The researched works mainly propose the use of foreign software systems to model the behavior of anchored structures, such as Simo, Riflex [5], MIMOSA [17], MOSES [18], ANSYS Aqwa [28] and next working with optimizing program to select an anchor mooring system. It is difficult to find a rigorous solution to the optimization problem with such division of functions. An integrated optimization procedure, an element of which is a comprehensive mathematical modeling of the behavior of the investigated object, is proposed in this work.

Mooring system optimization for a semisubmersible floating platform MOSS CS50 MK2, installed at a depth of 90 m in the area of the Kirinskoye gas condensate field to the East of the Sakhalin Island is considered as an example.

The platform is positioned at the drilling location by mooring system that includes 8 mooring lines. The mooring system is represented by 84 mm chains with a total length of 2130 m; the studded chain with NV P5 category with a breaking load of 8381 kN. The linear weight of the chain is 1.6 kN/m, Young's modulus is 0.58×108 kN/m. 3D geometrical model of the platform was prepared for the numerical modeling in software package “Anchored Structures”. It is shown in Fig. 1.

The external loads typical for a storm with 100-year return period were taken from Reference data on the regime of wind and waves of the Barents, Okhotsk and Caspian seas (The Russian Maritime Register of Shipping) to study the behavior of the platform in survival mode. The external conditions were accepted for extreme load mode in accordance with ND 2-020201-015 “Rules for the classification, construction and equipment of mobile offshore drilling units and fixed offshore platforms”. The rose of external loads has an asymmetry. Hull resistance coefficients were taken from the platform technical passport. Next, multiple time domain modeling of an extreme storm duration of 6 hours and from 8 different directions was performed. The behavior of the platform and extreme tensions in the mooring lines were investigated based on the modeling. On this basis, the mooring system was optimized using criterion (5).

In the initial position it was assumed that the azimuth angle of platform was 45°, the length of all mooring chains had maximum possible value of 2100 m. The mooring lines on the plan had the similar degree step of 45° and the first line has an angle of 22.5° with the longitudinal axis of the platform.

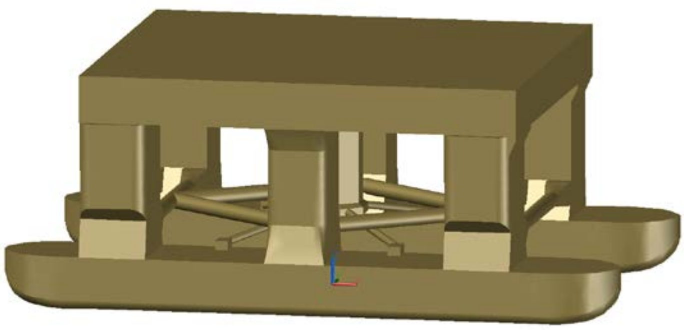

Figure 1. General view of platform geometrical model.

The first optimization step, associated with the search for the best tension of the lines (Fig. 2), showed that in the initial position the initial tension of 500 kN is the best value. The safety factor of the mooring lines with the initial configuration is on the edge of the permissible value (K_n = 1.5) according to ND 2-020201-015. The second optimization step (Fig. 3) showed that the maximum possible length of mooring lines is the minimum allowable one. Negative values in Fig. 2 and Fig. 3 appear when any of the restrictions from (4) are violated, which reduces the functional J_f so much that its value cannot pretend to be an extremum. The 135° azimuth angle of the platform was found to be the best based on the comparison of storms from different directions. Next the search for the best plan inclination angle of the line was performed. Only the first two angles are independent that is why the best values of the first two angles were determined: α_1 = 10.5, α_2 = 77.5 (other ones are determined on the basis of symmetry). The mooring system parameters which provide the safety factors for the tension of the mooring lines were obtained after the first cycle of the optimization procedure.

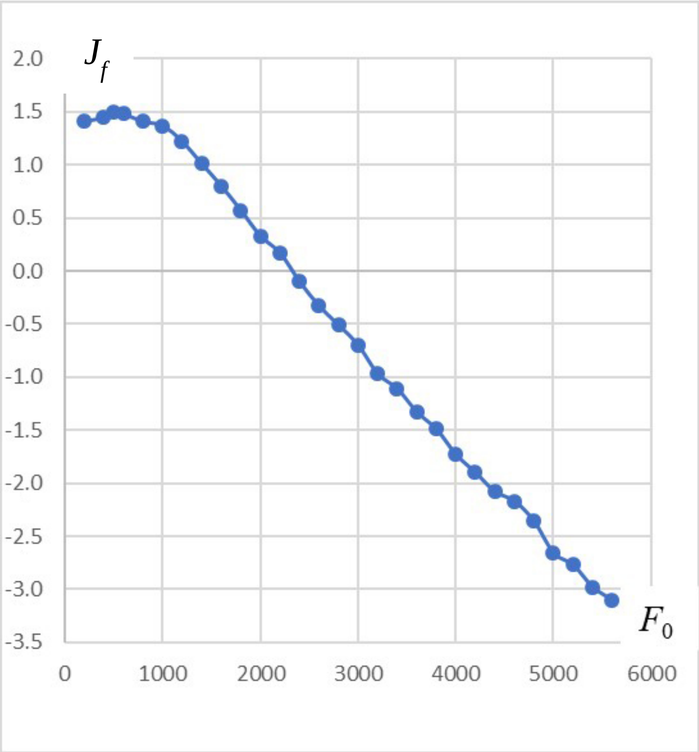

Figure 2. The value of the functional J_f at the first step of the initial tension optimization.

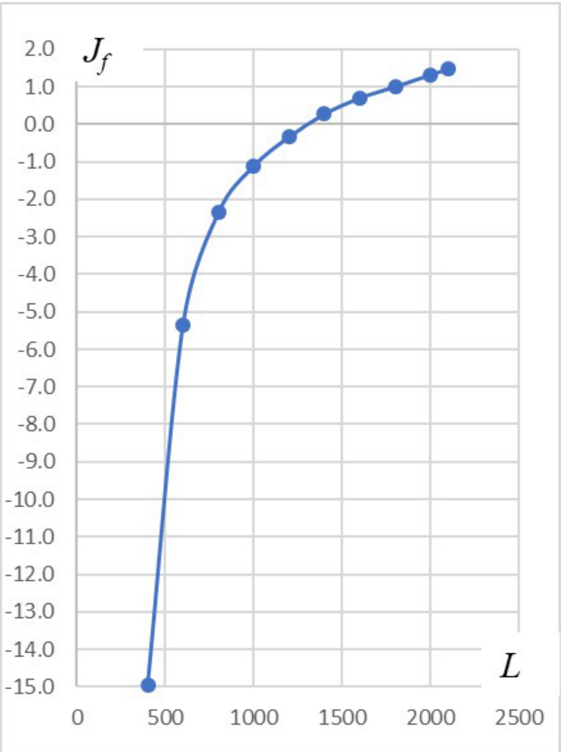

Figure 3. The value of the functional J_f at the first step of the line length optimization.

The initial values of the parameters obtained in the previous cycle were used in the second cycle of optimization. The newly obtained parameters of the platform positioning were determined by the following parameter values: the platform azimuth angle from 0° or 180° (the azimuth angle had little effect on the value of the optimality criterion: the worst safety factor for the lines tension varied within 1 % in the range of azimuth angles variation). The optimal initial tension is 450 kN, the length of the lines is 2100 m, the values of the independent plan inclination angles of the lines are α_1 = 10.5, α_2 = 87.5. Fig. 4 presents the comparison between the initial location of mooring lines and optimized one.

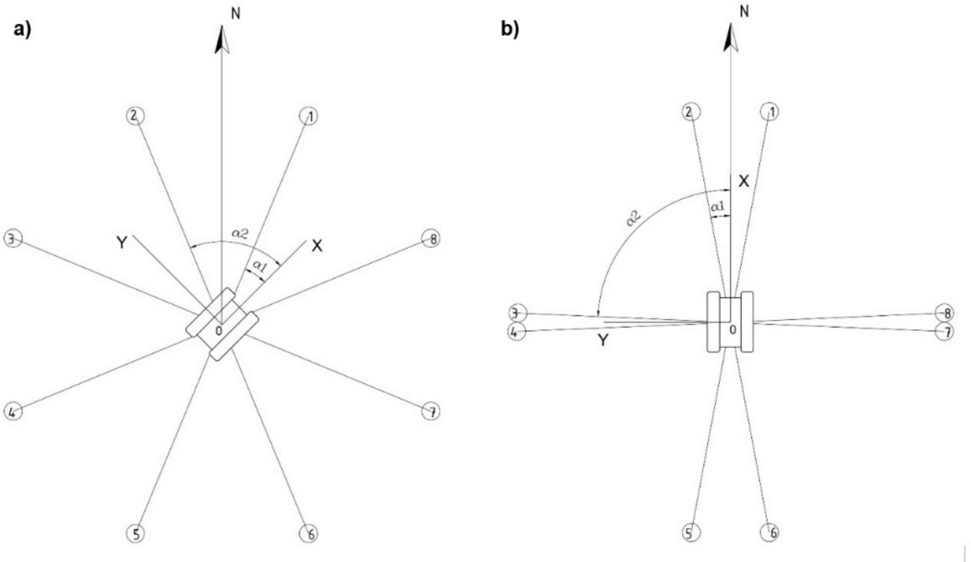

Figure 4. Location of mooring lines: a) — initial case; b) — optimized case.

According to the results of the second optimization cycle, the safety factors for the lines tension were obtained. Comparison of safety factors values are shown in Table 1.

Table 1. The lowest safety factor for tension in anchor lines.

Direction	Initial safety factors	Safety factors at the first optimization step	Safety factors at the second optimization step
N	**1.46**	1.66	**1.66**
E	1.53	1.68	1.67
S	1.50	1.68	1.80
W	1.62	1.75	1.79
NE	1.68	1.74	1.82
SE	1.75	1.64	1.82
SW	1.90	1.96	2.10
NW	1.70	**1.62**	1.81

Thus the optimization procedure in this example made it possible to determine the characteristics of the mooring system, when the initial value of the criterion safety parameter is improved by 10 % on the average, as well as made it possible to leave the boundary of the minimum permissible values of the safety factors for the tension of the mooring lines. The performed test calculation also confirmed the convexity of functional (5) and the convergence of the optimization procedure. The performed optimization procedure based on numerical experiments in the time domain, implemented in software package, makes it possible to abandon the fuzzy logic tasks presented in a number of works [14–17].

4. Conclusions

The problem of choosing the parameters of the mooring system that ensure the highest safety of the structure in operation is always emerge at the design phase of an offshore floating anchored structures or at the design phase of positioning it in offshore waters.

The problem of choosing the best parameters of mooring systems can be formulated in various ways, which can lead to multicriteria and multiparameter optimization problems. The solution of the problems of choosing the mooring systems parameters in the most complex formulation is possible using the methods of fuzzy logic, which allows finding acceptable solutions.

A variant of the formulation of mooring system optimization problem for floating anchored structure in survival mode is proposed in this article. This allows to find an exact optimal solution for the main parameters of the mooring system. A method for solving the problem of multiparameter optimization of the mooring system characteristics is proposed, which is implemented using existing software products that modeling the dynamics of offshore floating structures under the environmental loads.

5. Acknowledgements

The research is partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2020-934 dated 17.11.2020).

References

1. Shkhinek, K.N. and other. Gidrotekhnicheskie sooruzheniya na kontinentalnom shelfe [Hydraulic structures on the continental shelf]. Gidrotekhnika. [Hydraulic engineering. XXI century]. 2013. 4 (16). Pp. 48–56.
2. Elistratov, V.V. and others. The investigation of conceptual approaches to the creation of marine ice-resistant floating wind power plant. Proceedings of the International Offshore and Polar Engineering Conference. 2019. Vol. 1. Pp. 428–434.
3. Elistratov, V.V. and others. Proektirovanie i nauchnoe obosnovanie morskih vetroelektricheskih stancij [Design and scientific rationale of offshore wind power stations]. Nauchno-tekhnicheskiy sbornik RMRS [Research Bulletin of the Russian Maritime Register of Shipping]. 2014. No. 37. Pp. 77–85.
4. Tertyshnikova, A.S., Blagovidova, I.L., Kushnir, V.M. Parameters of the position system for the deep-water drilling platform. Vestnik SevNTU [Bulletin of SevNTU]. 2010. No. 106. Pp. 164–167.
5. Xu, K., Gao, Z., Moan, T. Effect of hydrodynamic load modelling on the response of floating wind turbines and its mooring system in small water depths. Journal of Physics: Conference Series. 2018. Vol. 1104. DOI:10.1088/1742-6596/1104/1/012006
6. Kolacio, I., Prpić-ORŠIĆ, J., Kurilić, K. Analiza sidrenja poluuronjive platforme scarabeo 7 [Analysis for Semisubmersible platform Scarabeo 7]. Brodogradnja [Shipbuilding]. 2010. 61 (1). Pp. 34–41.
7. Naumenko, A.A., Blagovidova, I.L., Pyanov, A.V., Ivanova, O.A. Numerical simulation of the positioning process of complex floating objects when performing offshore operations. Transactions of the Krylov state research center. 2019. No. S2. Pp. 239–247. DOI: 10.24937/2542-2324-2019-2-S-I-239-247
8. Ivanova, O.A., Kushnir, V.M., Blagovidova, I.L. Physical models of TLP and SPAR deepwater drilling platforms for experimental researches of the dynamics in the experimental basin. Vestnik SevNTU [Bulletin of SevNTU]. 2014. No. 153. Pp. 72–79.
9. Sabziyan, H., Ghassemi, H., Azarsina, F., Kazemi, S. Effect of Mooring Lines Pattern in a Semi-submersible Platform at Surge and Sway Movements. Journal of Ocean Research. 2014. Vol. 2, No. 1. Pp. 17–22. DOI:10.12691/jor-2-1-4
10. Sabziyan, H., Ghassemi, H., Azarsina, F., Kazemi, S. Appropriate Model for Mooring Pattern of a Semi-Submersible Platform. Journal of Subsea and Offshore. 2015. Vol. 1. Pp. 18–25.
11. Iqbal, M., Azam, M., Naeem, M., Khwaja, A.S., Anpalagan, A. Optimization classification, algorithms and tools for renewable energy: A review. Renewable and Sustainable Energy Reviews. 2014. No. 39. Pp. 640–654. DOI: 10.1016/j.rser.2014.07.120
12. Wu, B., Cheng, X., Chen, Y., Ni, X., Zhang, K. Design Automation of Mooring Systems for Floating Structures. Practical Design of Ships and Other Floating Structures. 2020. No. 65. Pp. 579–594. DOI: 10.1007/978-981-15-4680-8_40
13. Montasir, O.A., Yenduri, A., Kurian, V.J. Mooring System Optimisation and Effect of Different Line Design Variables on Motions of Truss Spar Platforms in Intact and Damaged Conditions. China Ocean Engineering. 2019. 33 (4). Pp. 385–397. DOI: 10.1007/s13344-019-0037-1
14. Monteiro, B.F., de Pina, A.A., Baioco, J.S., Albrecht, C.H., de Lima, B.S.L.P., Jacob, B.P. Toward a methodology for the optimal design of mooring systems for floating offshore platforms using evolutionary algorithms. Marine Systems and Ocean Technology. 2016. 11 (3-4). Pp. 55–67. DOI: 10.1007/s40868-016-0017-8
15. de Pina, A.C., de Pina, A.A., Albrecht, C.H., Leite Pires de Lima, B.S., Jacob, B.P. ANN-based surrogate models for the analysis of mooring lines and risers. Applied Ocean Research. 2013. No. 41. Pp. 76–86. DOI: 10.1016/j.apor.2013.03.003
16. Carbono, A., Menezes, I., Martha, L.F. Mooring Pattern Optimization using Genetic Algorithms. 6th World Congresses of Structural and Multidisciplinary Optimization. Brazil. Rio de Janeiro, 2005.
17. Shafieefar, M., Rezvani, A. Mooring optimization of floating platforms using a genetic algorithm. Ocean Engineering. 2007. 34 (10). 1413–1421. DOI: 10.1016/j.oceaneng.2006.10.005
18. Mirzaei, M., Maimun, A., Priyanto, A., Fitriadhy, A. Mooring Pattern Optimization Using A Genetic Algorithm. Jurnal Teknologi (Sciences and Engineering). 2014. 66 (2). 189–193. DOI: 10.11113/jt.v66.2519
19. Jin, H.Z., Su, X.Y., Yu, A.C., Lin, F. Design of automatic mooring positioning system based on mooring line switch. Dianji Yu Kongzhi Xuebao [Electric Machines and Control]. 2014. 18 (5). 93–98.
20. Xu, S.W, Liang, M.X, Wang, X.F, Ding, A.B. A Mooring System Deployment Design Methodology for Vessels at Varying Water Depths. China Ocean Engineering. 2020. Vol. 34, No. 2. Pp. 1–13. DOI: 10.1007/s13344-020-0018-4
21. Monteiro, B.D.F., Albrecht, C.H. and others. Optimization of mooring systems for floating offshore platforms considering seabed obstacles. Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. Norway. Trondheim, 2017. DOI: 10.1115/OMAE2017-61482
22. Monteiro, B.D.F., Baioco, J.S., Albrecht, C.H., de Lima, B.S.L.P., Jacob, B.P. Optimization of mooring systems in the context of an integrated design methodology. Marine Structures. 2021. Vol. 75. DOI: 10.1016/j.marstruc.2020.102874
23. de Pina, A.A., Albrecht, C.H., de Lima, B.S.L.P., Jacob, B.P. Tailoring the Particle Swarm Optimization Algorithm for the Design of Offshore Oil Production Risers. Optimization and Engineering. 2010. No. 12. Pp. 215–235. DOI: 10.1007/s11081-009-9103-5
24. Teslyaruk, I., Bolshev, A. Numerical analysis of behavior offshore anchored structures and improvement of systems of their holding. Proceedings of the Second International Conference on Mathematics and Computers in Sciences and in Industry. Malta. Sliema, 2015. Pp. 188–190. DOI: 10.1109/MCSI.2015.45
25. Teslyaruk, I., Bolshev, A. Technique optimization of holding systems of marine floating objects on the basis of numerical modeling of their behavior. International Journal of Mathematics and Computers in Simulation. 2016. Vol. 10. Pp. 72–76.

26. Amosov, A.A., Dubinskij, Y.A., Kopchenova, N.V. Vychislitelnye metody dlya inzhenerov [Computational methods for engineers]. Moscow: Vysshaya shkola. 1994. 543 p.
27. Bolshev, A.S., Kuteinikov, M.A., Frolov, S.A. Matematicheskoe modelirovanie povedeniya morskih plavuchih obyektov v programmnom komplekse «Anchored Structures» [Mathematical modeling of offshore floating objects in the software package «Anchored Structures»]. Nauchno-tekhnicheskiy sbornik RMRS [Research Bulletin of the Russian Maritime Register of Shipping]. 2013. No. 36. Pp. 68–90.
28. Gogin, A., Kantarzhi, I. Numerical Study of the Floating Gravity Base Structure Mooring. Proceedings of EECE 2019. Lecture Notes in Civil Engineering. 2020. Vol. 70. 205–219. DOI: 10.1007/978-3-030-42351-3_18

Information about authors:

Alexander Bolshev*, Sc.D. in Technical Science*
ORCID: https://orcid.org/0000-0002-0177-8389
E-mail: bolshev_as@spbstu.ru

Sergey Frolov*, PhD in Technical Science*
ORCID: https://orcid.org/0000-0002-1811-7712
E-mail: frolov_sa@spbstu.ru

Ekaterina Shonina,
ORCID: https://orcid.org/0000-0001-5292-7295
E-mail: shonina_ev@spbstu.ru

Received 15.02.2021. Approved after reviewing 04.06.2021. Accepted 16.06.2021.