Proceedings of the 25th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2019, Delft, The Netherlands

Mathematical Modeling of Ice Loads on Ship Hull in View of Their Stochastic Nature: Concept Definition & Studies Review

Vladimir V. YAKIMOV[1], Tatiana I. LETOVA[2]
[1] Bureau Hyperborea, Saint Petersburg, Russia
[2] Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russia

ABSTRACT

This article is of a conceptual nature and deals through the example of ice loads with the consideration of general issues related to researching the external environmental effects on marine infrastructure facilities under presence and influence of random components. Main directions and advantages for using the probabilistic approach to the design and analysis of ships and marine engineering units are determined. The brief description of simulation as a method for systems' research is given, and the multifaceted substantiation for applying the simulation technique in its probabilistic definition to solve the problems of assessing and forecasting the ice loads on marine infrastructure facilities is performed. The representative review of implemented national and foreign studies in the stated subject area is provided. The conclusion is drawn that the probabilistic approach to the determination of ice loads on ships and marine engineering units to the full extent conforms to the contemporary worldwide trends in researching the processes of their interaction with the external environment.

KEY WORDS: Probabilistic Method; Simulation; Ice Load; Ship; Marine Engineering Unit.

INTRODUCTION

It is known that any phenomenon in the environment, being physically reasonable and natural, contains the elements of randomness (Ekimov, 1975). At the same time, with regard to a specific problem, it should be taken into consideration how significant the influence of randomness is. In some problems, depending on phenomenon kind, study objectives, required solution accuracy, etc., the elements of randomness could be treated as secondary factors and not accounted, at that the neglect of randomness allows to obtain the results that to a sufficient extent comply with the practical purposes. In other problems, the elements of randomness act a highly important part, and disregarding them could lead to an incorrect assessment of phenomenon as a whole. Solving the problems that involve the account of random factors requires the use of probabilistic methods based on provisions of modern probability theory.

It should be noted that, despite the qualitative difference in the approaches to the description of phenomena, probabilistic and deterministic methods are closely linked and not only do not exclude, but also complement each other. Deterministic methods enable to perform the general statement of a problem and to determine the key direction of its solving with the use of apparatus of mechanics, physics, mathematics, etc., while probabilistic methods ensure introducing in a problem the elements of randomness and specific methods of their accounting. Furthermore, no engineering problem could be solved exclusively by means of probabilistic methods, without its initial consideration from the deterministic positions. On many occasions, the problem solving by means of probabilistic methods proper is not possible without the availability of deterministic algorithms (Ekimov, 1975).

USE OF PROBABILISTIC METHODS TO DETERMINE THE EXTERNAL FORCES ON MARINE INFRASTRUCTURE FACILITIES

The real-life processes of interaction between marine infrastructure facilities and external environment are of a pronounced stochastic nature. Their distinctive feature is the presence of a considerable number of various random components that directly influence on value of output interaction parameters. As a result, it seems reasonable to transit from the deterministic methods for finding the parameters under consideration to the appropriate probabilistic estimates.

In the national literature, the first references to the application of probabilistic approach to the design and analysis of engineering structures date from the end of the 1920s. The active penetration of probabilistic methods into the shipbuilding began in the 1950s, primarily for solving the problems of ship theory and ship structural mechanics. In particular, this milestone was facilitated by developing the methodological apparatus of theory of random processes, which allowed to consider the ship hull as a dynamic system subject to the exposure of stochastic perturbations. Although to a various extent, the elements of randomness are found with regard to all three fundamental problems of ship structural mechanics, at that they could be accounted quite strictly and in an explicit form by means of probabilistic methods. The use of given methods takes on particular significance for solving the first problem related to determining the external forces, since namely the randomness of external environmental conditions is usually the main cause defining the randomness of problem as a whole (Ekimov, 1966).

The essence of modern probabilistic methods for determining the external forces is as follows. The arbitrary load acting on hull as a whole or on its separate structure could be represented in the general case as a sum of two components that to a considerable extent differ from each other in the rate of in-time variation (Boytsov & Knoring, 1972):

$$Q_i(t) = Q_i^{st}(t) + Q_i^{var}(t), \qquad (1)$$

where $Q_i^{st}(t)$ is a static (or, more exactly, quasi-static) load component and $Q_i^{var}(t)$ is a variable (or fluctuational) load component.

The stated load division is based on profound differences in the physical and statistical nature of both components, the ratio of which could change within the wide range for certain conditions. The static load component has a negligible rate of in-time variation compared to the variable load component. Therefore, the value $Q_i^{st}(t)$ remains almost constant within the time interval Δt, which could be deemed sufficient to ensure the statistical representativeness of realizations of random process $Q_i^{var}(t)$. At the same time, within the whole totality of time intervals Δt (i.e. during the long-term facility operation), the component $Q_i^{st}(t)$ could be considered as a random process, the statistical properties of which do not depend on factors defining the statistical properties of component $Q_i^{var}(t)$. The variable load component has a quite high rate of in-time variation and constitutes a random process within the each time interval Δt, which is in the general case non-stationary. However, it is assumed that the changes in the probabilistic characteristics of random process $Q_i^{var}(t)$ within the time interval Δt are sufficiently small compared to the random changes in the load proper, therefore it is allowed to identify the process under consideration as quasi-stationary.

When solving the corresponding problems, the use of probabilistic methods provides the possibility to take into account most completely and reliably the actual conditions of facility operation distinguished by complexity, variability and multiplicity. In addition, the given methods are rather efficient when performing the comparative calculations, due to which the influence of certain deviations from the proven solutions could be assessed with the similarity of initial assumptions and on basis of accumulated experience in the shipbuilding. They also serve as a powerful tool for theoretical research and enable to reveal the objective principles reflected in the conventional calculation methods (Bronskiy, et al., 1974).

APPLICATION OF SIMULATION TECHNIQUE TO RESEARCH THE COMPLEX SYSTEMS

In the general form, the simulation could be defined as a method for system's research through the system's simulation model that combines the salient features of experimental approach and specific conditions of computing machinery use. In the opinion of authors of this paper, the stated definition to the greatest extent reveals the essence of simulation, because, firstly, it focuses on experimental nature of method and, secondly, emphasizes the need to apply the computer technologies for its implementation.

The systems being studied at the present time are mostly characterized by a large number and variety of components and connections between components. Therefore, the complex systems almost completely eliminate the possibility to research them with the use of mathematical models assuming the known analytical solutions that are formally acceptable and accessible to get. In this case, it is required to resort directly to the simulation, which is perceived, on frequent occasions, as a "last hope method" and "rough power hit" (Shannon, 1975).

The following main advantages of simulation contribute to its widespread occurrence in the processes of researching the complex systems:

• simulation allows for a real system to evaluate its functional parameters under any changes in the operation conditions and for a potential system to compare its alternative implementation forms or its alternative application strategies in order to select the optimal project;

• simulation allows to research a system under uncertainty conditions, i.e. in the absence of complete or exact information about it;

• simulation allows when considering a dynamic system to investigate the long interval of its functioning within the short time frame or, conversely, to analyze its operation in much more detail in the extended time period.

Furthermore, with regard to the most part of modern systems, the simulation technique in its probabilistic definition is provided as the only possible method for their research due to the objective presence and influence of randomness factor (Law & Kelton, 2000).

In the course of simulation, it is customary to mark out four key components, including the real or potential system being studied, the conceptual (i.e. logical and mathematical) system's model, the software (i.e. simulation) system's model and the computing machinery complex intended to implement the targeted computational experimentation. All simulation models belong to the models of "black box" type, i.e. provide for delivering the output signal of system when arriving the input signal to its interacting subsystems. The structure of simulation models could be to a considerable extent complicated, but the fundamentals for its building are rather trivial. In the general form, the structure of simulation model is described mathematically as follows (Shannon, 1975):

$$E = f\left(x_i, y_j\right), \quad (2)$$

where E is an effect of system's action; x_i are externally controlled variables and parameters; y_j are externally non-controlled variables and parameters and f is a functional dependence between x_i and y_j defining the value E.

The system's research by means of simulation technique is a complex sequential-iterative process, which, regardless of type of simulation model, could be represented as a certain totality of separate stages (see Figure 1).

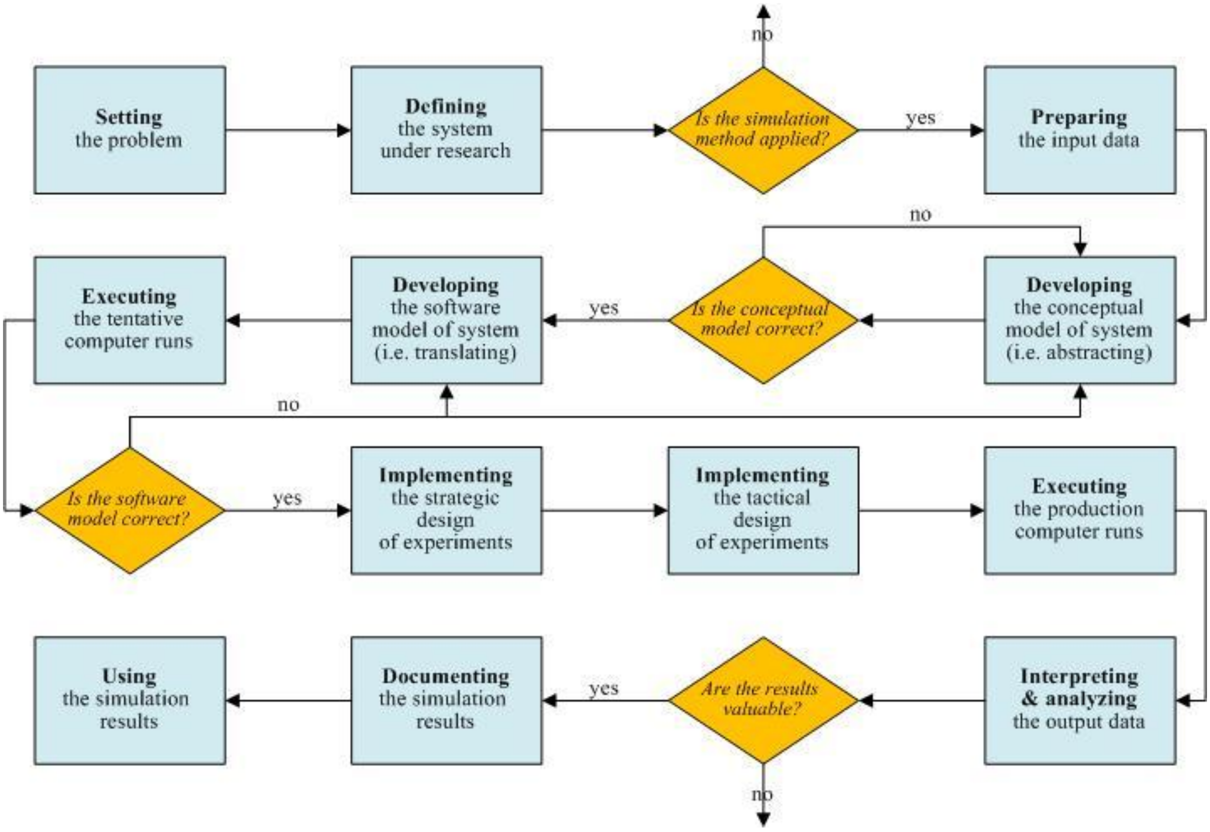

Figure 1. System's research by means of simulation technique

The rapid development of computer engineering and information technologies has predetermined the intensive introduction of simulation as a method for researching the complex systems. After receiving the initial impetus during the implementation of aerospace programs, the simulation finds a qualitative application in the modern world in almost all fields of human activity. Its use appears most efficiently when solving the problems related to the design, performance analysis and modernization of manufacture, computer, transport, finance and economic, armament, communication, management, mass service and other complex systems. Finally, it should be noted that the application of simulation technique in its probabilistic definition takes on particular significance at the different life cycle stages for marine infrastructure facilities in order to assess and forecast the external environmental (wave, wind, ice, etc.) effects being of a stochastic nature.

MODELING OF STOCHASTIC ICE LOADS ON MARINE INFRASTRUCTURE FACILITIES

Depending on class of marine infrastructure facilities accepted for consideration, the studies concerning the modeling of stochastic ice loads could be divided into two main directions. The first direction covers ice effects on marine engineering units intended for operation in the ice conditions, primarily, on offshore ice-resistant platforms of various architectural and structural types. The second direction involves ice effects on ice-going ships. Ultimately, the class of marine infrastructure facilities identifies the specific mechanism of their interaction with the ice cover, including the loading rate, model for ice deformation and failure, etc. According to the traditional approach, in the first case, the marine engineering unit remains motionless in operation, and the ice cover drifts with the quite low speed. At that, in the second case, the ice cover is conventionally assumed to be motionless, since the speed of its drift is negligible compared to the speed of ship motion in ice. In the contemporary national practice, the studies related to the stochastic ice effects on marine engineering units have become more widespread occurrence.

The large-scale comprehensive studies of issues concerning the simulation of stochastic ice effects on continental shelf structures are conducted at the School of Engineering of the Far Eastern Federal University under supervision of Aleksandr Bekker. The specialists of the University suggested the concept for forming the ice loads on offshore ice-resistant platforms taking into account the in-time variability of parameters of ice regime in the water areas and the particularities of interaction of ice cover with the structures. Based on given concept, it was succeeded to perform the probabilistic statement of problem under consideration. Following the results of theoretical and experimental studies, the simulation model for process of mechanical interaction of marine engineering units with the drifting level ice fields and drifting hummocked ice formations was developed and tested. The use of simulation model allowed to determine the distribution functions for maximum ice loads that are required to assess the operational reliability of structures (Bekker, 1998).

It should be noted the multi-year studies carried out at the Division of Structural Strength and Reliability of the Krylov Shipbuilding Research Institute under supervision of Oleg Litonov and focused on development, improvement and practical implementation of probabilistic and statistical methods to describe the ice conditions and to analyze the ice effects on marine engineering units. The results of conducted studies provided, among others, the basis for currently valid requirements of national regulatory documentation in terms of assignment and standardization of design ice loads acting on structures of offshore ice-resistant platforms. Thus, as design ice loads under extreme loading, there are considered the probable of maximum ice loads that could effect for a 100-year period (with regard to the fixed offshore platforms) or for the entire operation period (with regard to the mobile offshore drilling units). They are characterized by exceedance probability in the long-term distribution assumed to be 10^{-8}. At that, as design ice loads in the operation conditions, there are accepted the ice loads having the occurrence frequency equal to once a year and the exceedance probability in the long-term distribution equal to 10^{-6} (RMRS, 2018).

Timofeev (2002) summarized the results concerning the development and practical testing of simulation-stochastic model for determining the probabilistic characteristics of local ice loads acting on offshore ice-resistant stationary platform being a metal caisson installed in the center of the Prirazlomnoye oil field. The basic components of proposed model involve the stochastic model of external environment and the deterministic model of mechanical interaction between technical object and external environment.

The specialists of the Peter the Great Saint Petersburg Polytechnic University are also engaged in the studies of issues concerning the building and application of probabilistic model for ice loads acting on continental shelf structures. Within the framework of suggested concept, the methodological apparatus of international standard ISO 19906 “Petroleum and natural gas industries – Arctic offshore structures” is widely used to determine by calculation the ice load parameters (Bolshev, et al., 1997). Zvyagin (2015) considered the approach to the probabilistic modeling of ice pressure on marine engineering units not associated with the simulation of mechanical interaction of ice cover with the structures. According to the given approach, the ice pressure is represented as a random variable (or a random process) depending only on stochastic parameters of ice regime.

Through the example of ice loads, the specialists of the Vedeneev All-Russia Research Institute of Hydraulic Engineering investigated the different ways for describing and accounting the uncertainties of stochastic external environmental effects on continental shelf structures when using the probabilistic methods to assess their reliability (Kaufman, et al., 2018).

At the Ship Structure Department of the Leningrad Shipbuilding Institute, the studies on probabilistic simulation of ice loads acting on ship hull were started in the second half of the 1980s, and this activity was predominantly associated with Vladimir Kurdyumov. He performed the general statement of problem under consideration, partly developed the theoretical provisions of method for modeling the stochastic ice loads and formulated the basic principles for designing and implementing the probabilistic computer experimentation within the framework of given problem. In the early 1990s, the active works in the stated direction were suspended. However, the research subject has retained its topicality and significance in the course of time, and in 2009, the studies of corresponding issues were resumed at the Saint Petersburg State Marine Technical University under initiative of Vladimir Tryaskin. In 2012, it was submitted the holistic concept for reproducing the ice loads acting on ship hull in view of their stochastic nature based on combination of probabilistic and simulation approaches (Tryaskin, et al., 2012). The definition of simulation models for estimating the random values of physical and mechanical characteristics of ice cover (Yakimov & Tryaskin, 2013) and for estimating the random values of attainable (i.e. complying with the ice performance requirements) speed of ship motion in ice (Yakimov & Erkayev, 2016) was completed in 2013 and in 2017, respectively. The developed solution in terms of probabilistic simulation of ice loads acting on ship hull provides the basis for thesis research of Vladimir Yakimov.

In summary, for today, it is developed under direct participation of authors of this paper the inventive methodological and algorithmic support that is intended to implement the probabilistic simulation of ice loads acting on ship hull. It is based on interdisciplinary approach involving the integration of solutions in the field of ice physics, ice performance and ice strength. The practical testing of proposed method for modeling the stochastic ice loads applied to the set of the Arctic oil tankers with a deadweight of approx. 17 kt, 42 kt and 70 kt has mainly confirmed its adequacy and performability. The obtained simulation results in the area of substantiated exceedance probability have showed the acceptable correlation with the deterministic values of the same ice load parameters calculated according to the requirements of “ice” sections of regulatory documentation, including the Rules of the Russian Maritime Register of Shipping and the International Association of Classification Societies. Within the framework of ongoing project, the works on building, debugging and testing of special-purpose software as well as on verification of developed solution as a whole continue to be executed.

At the present time, the studies on modeling of stochastic ice loads on ships being to a sufficient extent similar to the studies of authors of this paper are actively conducted by specialists abroad, in particular:

• at the Department of Mechanical Engineering of the Aalto University under supervision of Pentti Kujala;

• at the Department of Marine Technology of the Norwegian University of Science and Technology under supervision of Bernt Leira;

• at the Faculty of Engineering and Applied Science of the Memorial Newfoundland and Labrador's University under supervision of Ian Jordaan, Faisal Khan and Brian Veitch.

To the obvious advantage of foreign studies in the stated direction, it should be referred the possibility to apply (e.g. for comparative analysis or solution verification) the data bases containing a considerable amount for information about the results of measuring the ice load parameters in the actual conditions of ship navigation in ice (Kotisalo & Kujala, 1999; Leira, et al., 2009; Suominen, et al., 2013).

Two principal approaches to the modeling of stochastic ice loads on marine infrastructure facilities accepted for use are illustrated in Figure 2 and in Figure 3. The first approach considered by Sanderson (1988) comprises the probabilistic model of external environment and the deterministic model of mechanical interaction of ice cover with the structures. Within the framework of second approach considered by Daley (1991), both models are probabilistic.

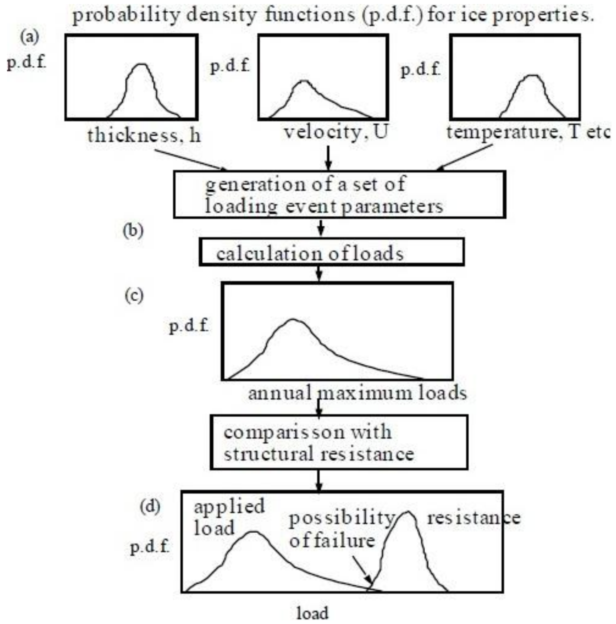

Figure 2. Modeling of stochastic ice loads according to Sanderson (1988)

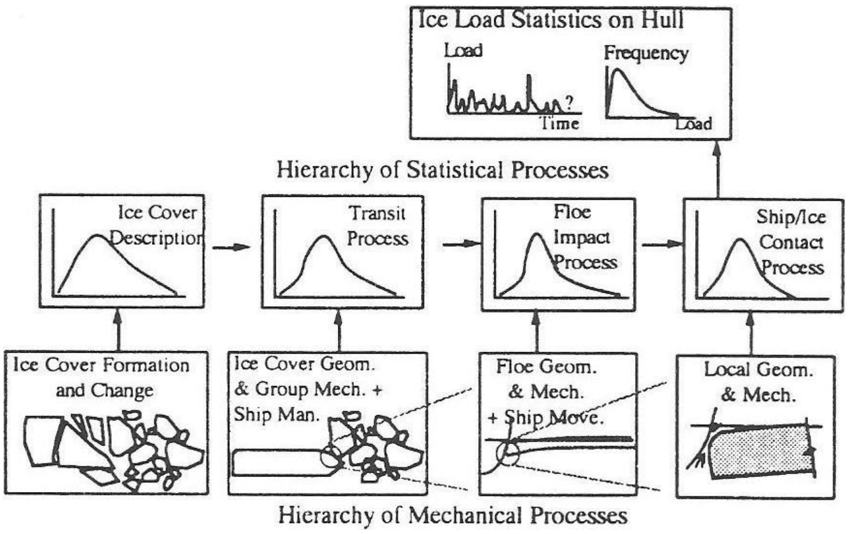

Figure 3. Modeling of stochastic ice loads according to Daley (1991)

CONCLUSIONS

In the present article, the following general issues were considered related to researching the external environmental effects on marine infrastructure facilities under presence and influence of random components:

• main directions and advantages for using the probabilistic approach to the design and analysis of ships and marine engineering units were determined;

• brief description of simulation as a method for systems' research was given;

• multifaceted substantiation for applying the simulation technique in its probabilistic definition to solve the problems of assessing and forecasting the ice loads on marine infrastructure facilities was performed;

• representative review of implemented national and foreign studies in the stated subject area was provided.

Based on information cited above, it should be concluded that the probabilistic approach to the determination of ice loads on ships and marine engineering units to the full extent conforms to the contemporary worldwide trends in researching the processes of their interaction with the external environment.

REFERENCES

Bekker, A.T., 1998. *Development of Methods for Calculating the Probabilistic Characteristics of Ice Loads to Assess the Reliability of Continental Shelf Structures.* Habilitation Thesis: Far Eastern State Technical University. (In Russian).

Bolshev, A.S., Chasovskikh, E.V., Frolov, S.A., Shkhinek, K.N. & Karna, T., 1997. Probabilistic Model of Ice Loads on Russian Arctic Offshore Structures. *Proceedings of the 16th International Conference on Offshore Mechanics and Arctic Engineering – OMAE 1997*, 1-B, pp. 159-164.

Boytsov, G.V. & Knoring, S.D., 1972. *Strength and Performability of Hull Structures.* Sudostroyeniye: Leningrad. (In Russian).

Bronskiy, A.I., Glozman, M.K. & Kozlyakov, V.V., 1974. *Fundamentals for Selecting the Ship Hull Structures.* Sudostroyeniye: Leningrad. (In Russian).

Daley, C.G., 1991. *Ice Edge Contact – A Brittle Failure Process Model.* Ph.D. Thesis: Helsinki University of Technology.

Ekimov, V.V., 1966. *Probabilistic Methods in the Ship Structural Mechanics.* Sudostroyeniye: Leningrad. (In Russian).

Ekimov, V.V., 1975. *Reliability of Structures Considering the Random Factors: Study Guide.* LSI: Leningrad. (In Russian).

Kaufman, B.D., Andrianova, Ye.A. & Albert, I.U., 2018. Consideration of Uncertainties When Assessing the Reliability of Offshore Structures Against Environmental Effects Using Different Procedures. *Proceedings of the Vedeneev All-Russia Research Institute of Hydraulic Engineering*, 289, pp. 68-75. (In Russian).

Kotisalo, K. & Kujala, P., 1999. Ice Load Measurements Onboard MT Uikku During the ARCDEV Voyage. *Proceedings of the 15th International Conference on Port and Ocean Engineering under Arctic Conditions – POAC 1999*, 3, pp. 974-987.

Law, A.M. & Kelton, W.D., 2000. *Simulation Modeling and Analysis: Third Edition.* McGraw-Hill Companies Inc.: New York.

Leira, B.J., Børsheim, L., Espeland, Ø. & Amdahl, J., 2009. Assessment of Ice-Induced Loads on Ship Hulls Based on Continuous Response Monitoring. *Proceedings of the 2nd International Conference on Marine Structures – MARSTRUCT 2009*, pp. 345-354.

Russian Maritime Register of Shipping (RMRS), 2018. *Rules for the Classification, Construction and Equipment of Mobile Offshore Drilling Units and Fixed Offshore Platforms. Part II. Hull.*

Sanderson, T.J.O., 1988. *Ice Mechanics: Risks to Offshore Structures.* Graham & Trotman: London.

Shannon, R.E., 1975. *Systems Simulation: the Art and Science.* Prentice-Hall Inc.: Englewood Cliffs, New Jersey.

Suominen, M., Kujala, P., von Bock und Polach, R. & Kiviranta, J., 2013. Measured Ice Loads and Design Ice Loads. *Proceedings of the 4th International Conference on Marine Structures – MARSTRUCT 2013*, pp. 119-124.

Timofeev, O.Ya., 2002. *Forecasting of Reliability Indices for Ice Belt Structures.* Habilitation Thesis: Saint Petersburg State Marine Technical University & Arctic and Antarctic Research Institute. (In Russian).

Tryaskin, V.N., Yakimov, V.V. & Besse, P., 2012. Simulation of Ice Loads on Ship Hull. *Proceedings of the 22nd International Offshore and Polar Engineering Conference – ISOPE 2012*, 1, pp. 1215-1222.

Yakimov, V.V. & Tryaskin, V.N., 2013. Use of the Stochastic Simulation Technique for Estimation of the Ice Cover Strength by Interaction with Ship Hull. *Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions – POAC 2013*, 071.

Yakimov, V.V. & Erkayev, R.I., 2016. Development of Probabilistic Simulation Model for Estimating the Ship Speed in Ice According to the Ice Performance Requirements. *Theses of the Annual Industry Scientific and Technical Conference for Young Scientists and Specialists*, pp. 66-69. (In Russian).

Zvyagin, P.N., 2015. A Method for the Probabilistic Modelling of Ice Pressure. *Cold Regions Science and Technology*, 118, pp. 112-119.