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Nondestructive Testing of Ship Hulls Made of Composite Materials Using Acoustic Methods

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Abstract—A technique for the nondestructive testing of ship hulls that are made of composite materials in the process of their operation is considered. The study was performed using the impedance method and the free-vibration method taking the peculiarities of the test-object design into account. The results are presented.

Keywords: nondestructive testing of ship hulls from composite materials, impedance method of nondestructive testing, free vibration method, lamination-type inner flaws

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According to the practice of world navigation, one of the reliable criteria for the evaluation of the operational strength and lifetime of a ship hull is the dynamics of the development of different operation flaws and wear. The development of flaws in a hull structure yields a decrease in its strength characteristics and degrades its ability to resist unfavorable operational actions. When a flaw or wear reaches a certain size the stresses that act in the structure in their vicinity exceed the admissible ultimate strength that is specified by the ship designer or manufacturer. This can lead to both structure damage under calculated motion modes and a disproportional increase of the emergency damage zone in worst-case situations. Both cases have taken and often take place on the waterways of Russia [8, 9].

As distinct from other materials that are used for fabricating ship hulls, layered composites (fiberglass plastic) practically do not change their surface appearance and sizes in the process of aging, but lamination-type inner flaws are often formed in them. In some cases, an aged delaminated fiberglass plastic with a refurbished coating looks almost like a new material. Therefore, there is no point in analyzing variations in the geometric dimensions of the cross section of a structure that is made of composite materials in the process of its operation.

The existing method used by oversight bodies for determining the technical state of a ship hull that is made of composite materials in the process of operation is based only on a visual external examination. In accordance with the Provisions of the Russian River Register, the technical state of a plastic hull is recognized to be faulty if the shell is laminated, the premoulds exfoliate from the shell and components, and if there are cracks in the shell and in the components [8, 10].

Ship structures made from composite materials are formed from multilayer nonmetal materials, light plastic foams included. The elasticity modules, densities, and wave resistances of these materials can differ by tens of times. In addition, polymer composite materials that are used for fabricating ship hulls are characterized by large damping of ultrasonic waves, structural inhomogeneity, and substantial elastic anisotropy. Multilayed structures have several material interfaces with different acoustic properties. In this case, separate layers often have minor cracks (0.2 + 0.1 mm). The observation of the development of inner lamination-type flaws in the process of operation, which is performed with different nondestructive testing methods, makes it possible to evaluate variations in the mechanical properties of composite materials [2].

The development of the norms of the designed operational feasibility of the structure from the standpoint of existing flaws is closely connected with the problem of forecasting the dynamics of flaw development in the process of operation and parallel changes in the structure strength (namely, its deterioration).

In order to perform nondestructive testing, all ship bracings can be divided into two main structural groups (Fig. 1): the outer shell, deck platings, and platforms and the bulkhead panels and longitudinal and transverse components (the vertical keel, stringers, floors, frames, and beams).

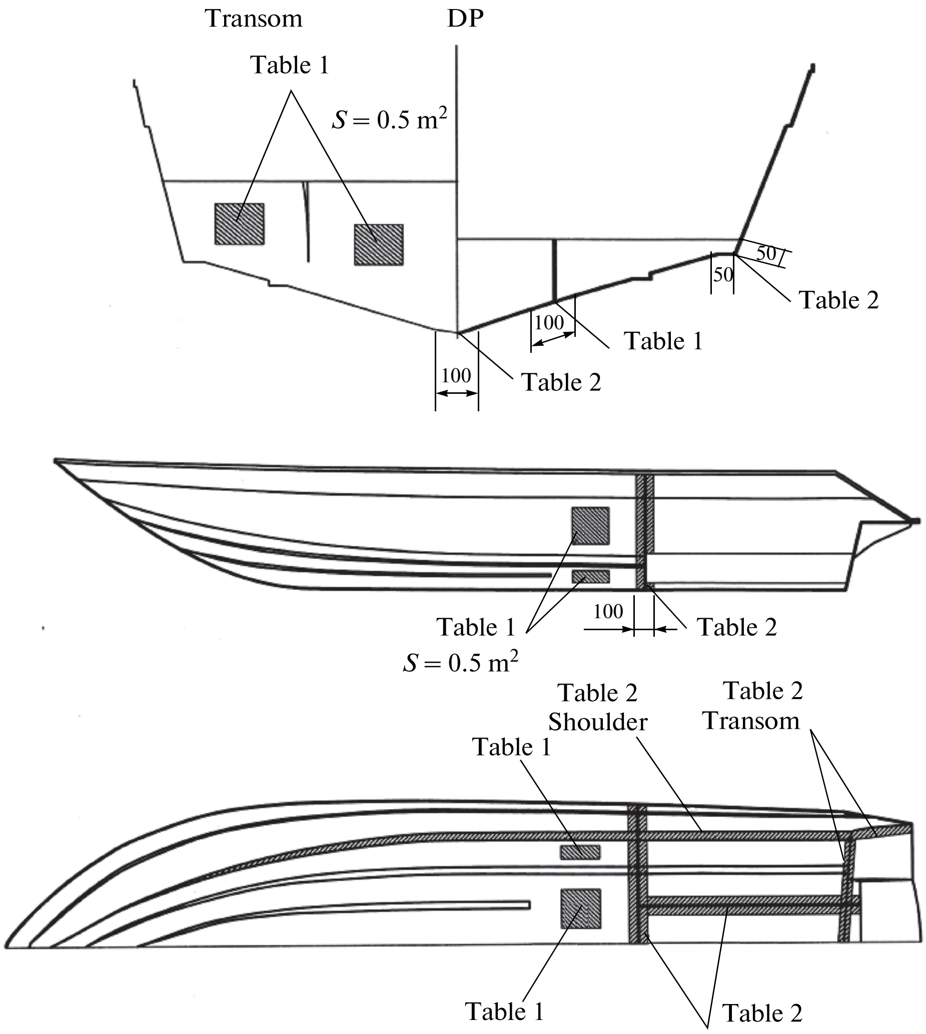

Fig. 1. Positioning of the sections of the 1st and 2nd structure groups on a ship hull made of composite materials.

The admissible flaw norms for each separate group can be specified individually. In this case, only flaws that lead to no more than a 10–15% deterioration of the physical-mechanical characteristics of the composite material can be considered admissible [6].

This technique for inspecting ship hulls that are made of composite materials using acoustic nondestructive methods is aimed at revealing the following flaws in different structural elements:

Laminations between the layers of a reinforcing material in the form of gas-filled cavities;

Laminations in the form of sections with unimpregnated or poorly impregnated layers of reinforcing material;

Laminations between middle layers and shells;

Laminations between a decorative layer and the component itself;

Laminations in the contact points both over the contact plane between the connected elements and connectors (straps, premould squares) and in the connectors themselves.

All these flaws can be detected using different nondestructive testing methods; however, preference is given to acoustic ones. Acoustic methods are considered to be the most promising group of nondestructive testing methods. Their widespread occurrence all over the world is explained by engineering, economical, ecological, and other considerations.

Echo methods, namely echo-shadow, echo-mirror, mirror-through-transmission, impedance, and velocimetric methods, and the method of free (proper) vibrations were considered as source methods for nondestructive testing aimed at detecting lamination-type flaws in multilayer ship hull structures that are

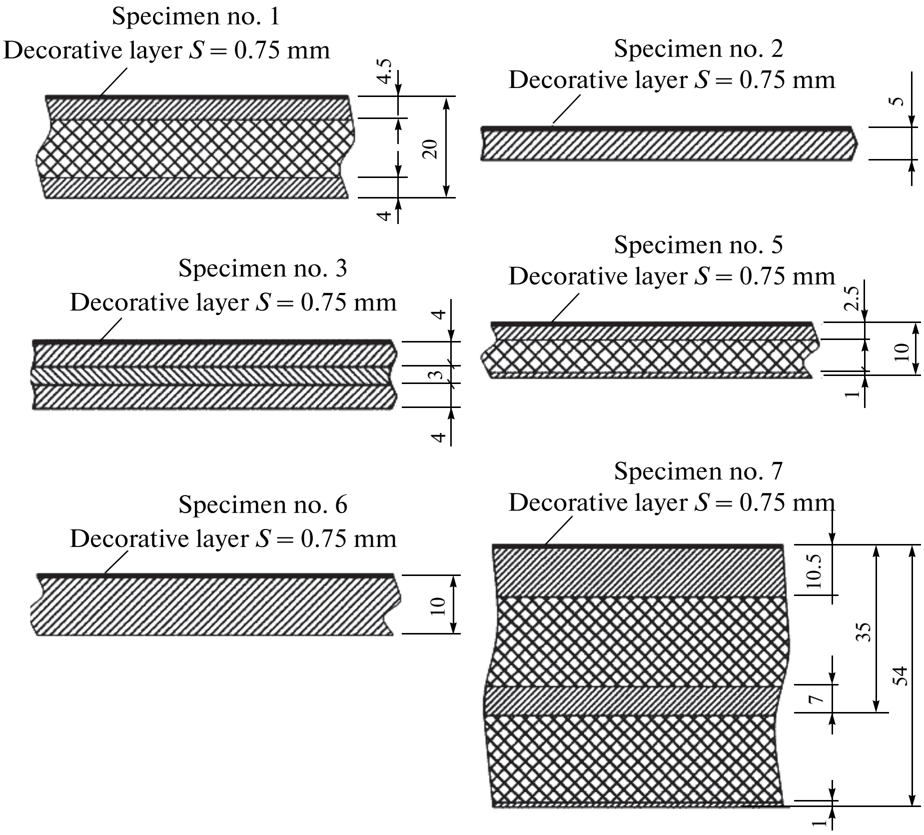

Fig. 2. Cross sections of different sections of a ship hull made from composite materials.

made of different composite materials. In this case, the application of echo methods under the conditions of unidirectional access to the hull surface (only from the outer side) is possible using reflection (the echo-shadow, echo-mirror, and mirror-through-transmission) methods [1].

When considering test-object specimens in the form of separate elements of a ship hull that are made of composite materials (Fig. 2), it can be expected that the depth of occurrence of the detected flaws is in the range of 0.75–15 mm.

Since ship hulls that are made from composite materials have guaranteed geometric sizes only over one (the outer) surface, the application of echo methods that are based on the signal reflection at the second surface can lead (without special studies) to inadequate interpretation of the test results and the decisions taken based on them will be erroneous. In addition, echo methods are difficult to implement if a test object has a large number of curvilinear surfaces (the hull of a high-speed ship is such an object). The peculiarity of the echo methods is the impossibility of performing testing at depths of 3–5 mm from a surface (with the total thickness of the hull shell for ships of the analyzed type are not greater than 5–8 mm in some places). Therefore, the impedance method and the local free-vibration method (see table, [5]) were accepted as the base methods for nondestructive testing of the flaws in multilayer ship hull structures that are made of composite materials. The ДАМИ-С flaw detector for composite materials is used as a device that performs both methods (Fig. 3) [3, 4].

Both inner lamination-type flaws that are positioned inside the structural element and zones where the joints of separate elements with the rest of the structure are damaged can be detected in multilayer ship structures that are made of composite materials. Nondestructive testing of the ship structure is performed from the side of the layer that is characterized by lower rigidity, i.e., a decorative layer. As a rule, lamination-type flaws cause changes in the signal that are beyond the aforementioned spread, which helps one to reveal them. The levels of signals from a moving or a fixed probe differ somewhat due to frictional noises that are caused by the interaction of the probe emitters with irregularities of the test object surface.

This difference increases with an increase in the scanning rate and the degree of surface roughness. When performing nondestructive testing of the ship hull sections with smooth surfaces, the effect of fric-

A comparison of the characteristic of acoustic nondestructive-testing methods

Method	Detected flaws	S min, mm^2	h max, mm	h min, mm	Drawbacks	Additional data
Impedance method with dual probe	Laminations, unsizings	4.0	15.0	0.2	Opposite direction of changes in the signal level upon detecting of nearby (0.2–0.5 mm) flaws	
Free-vibration method	Laminations, unsizings	100–1500	30	0.5	Noise upon testing	Difficult-to-apply on vertical surfaces; inapplicable on ceiling surfaces

tional noises is negligible and the scanning rate can be increased. As the roughness increases, frictional noises are intensified and the scanning rate should be reduced. This is determined experimentally for the difference in the signals from a fixed and a moving probe to be acceptable for testing. As a rule, a ship hull has sections with varying roughness. The scanning rate has to be changed to take this difference into account.

To reveal lamination-type flaws in multilayer ship hull structures that are made of composite materials in the process of nondestructive testing, a combination of two acoustic methods is used, namely the impedance method with a dual probe and the local free-vibration method.

The local free-vibration method is used for rapid inspection of extensive sections of the test object with a resolution of one measurement per one cm^2. When the testing is performed with a ДАМИ-С flaw detector using this method, an ÈÏÓ-1 probe is employed. It produces uniform normalized impacts on the surface under inspection; the response is recorded using reference-free settings of the flaw detector.

The local free-vibration method helps one to determine the position and the approximate configuration of the flaws, including deep ones (to 30 mm). In addition, this method makes it possible to perform row-wise scanning of large areas in order to reveal flaws with sizes from 1 cm^2 and then to construct their images on the screen of the device using interpolation. The zones of flaw positioning are represented on the device display with binding to the coordinate grid with a 1 × 1cm cell.

The impedance method of nondestructive testing with a dual probe (Fig. 4) includes two modes: point testing and threshold testing with an acoustic scanner; reference-free settings of the device are used.

Fig. 3. A portable ДАМИ-С flaw detector.

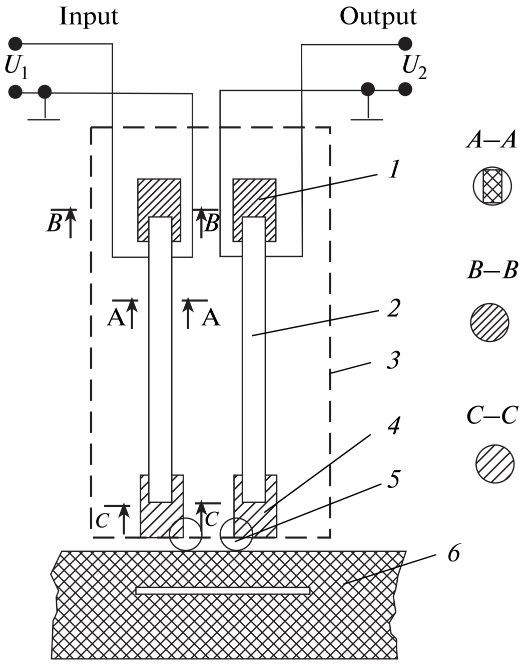

Fig. 4. A schematic of the detection of an inner lamination-type flaw with an impedance flaw detector with a dual probe.

At the stage of point testing, a ДАМИ-С that is operated in the normal mode detects the exact places of inner flaws. At the stage of threshold testing, a ДАМИ-С that is operated in the normal mode allows one to obtain C images of the inner flaws with an acoustic scanner. The ДАМИ-С device allows the determination of flaw sizes and measurement of the flaw area. Having been fixed, the images are stored in the memory of the device. Later, the specially developed ДАМИ-С Inspector Workstation software transfers the accumulated data (flaw images included) into the computer memory for further analysis, storage, and formation of the testing protocol.

When threshold testing mode is used, the data on the layer that the flaw was detected in, an image of the scanned section with the coordinate axes graded in millimeters, and the current position of the probe on the scanned section are displayed.

When a flaw is detected, a corresponding surface of area whose size is equal to the sampling increment along the corresponding axis is “blackened” on the display. The probe path is bright grey. The testing is simultaneously preformed in three layers and the data on each analyzed layer is displayed in turn. When the scanning is over, all faulty regions that are detected on the scanned section in this layer are marked on the display.

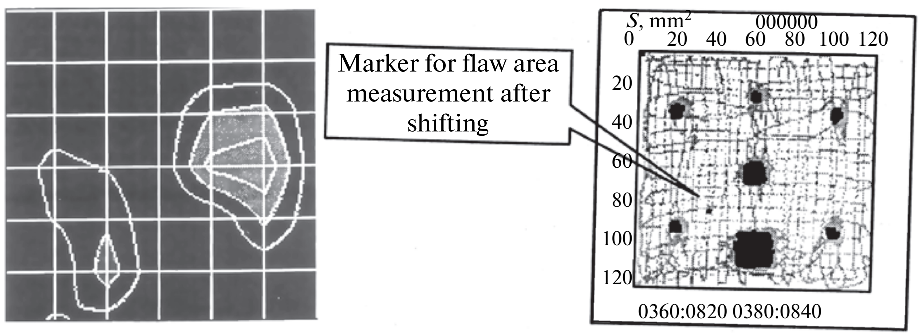

Fig. 5. Flaw images that were obtained using the free-vibration method (to the left) and the impedance method of threshold testing (to the right).

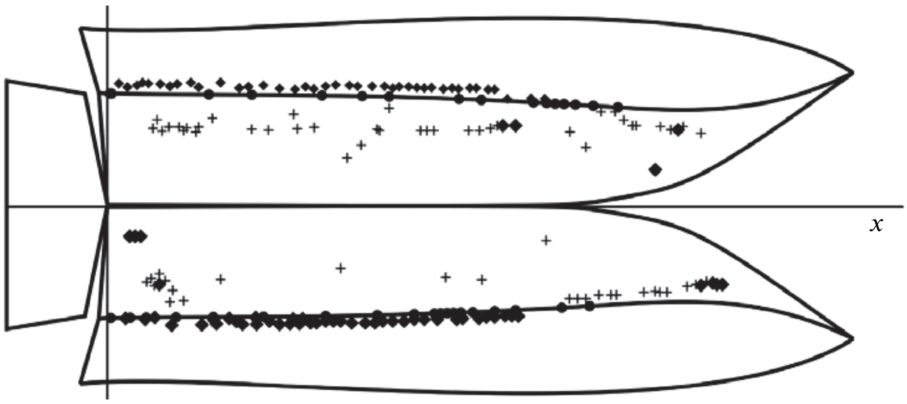

Fig. 6. Schematic of flaw positions on a ship hull made of composite materials, which were obtained based on the results of nondestructive testing.

The mode of threshold testing that is performed using an acoustic scanner allows one to obtain a full image of the faulty section of the test object for further measurement of flaw areas and their comparison with the fitness standard (see Fig. 5). The figure also shows the paths of the probe motion and positions of the detected flaws displayed by the device. The flaw detector modes allow determination of the sizes of flaws based on their images.

A normative document that regulates the inspection procedures for ship hulls made of composite materials in order to reveal operational flaws has been developed. This document is named A temporary technique for inspecting hulls of ships with a dynamic support (gliders) using nondestructive testing methods to detect lamination-type flaws. It was approved for application by a letter from the Central Administrative Board of the Russian River Register no. 07-01.9-153 as of January 24, 2007.

At present, the work of detecting flaws of ship hulls that are made from composite materials older than 5 years and that are operated under the engineering supervision of the Moscow Branch of the Russian River Register is occurring. The inspected ship hulls that are made of composite materials are over 20 meters in size. This work is accompanied by analytical and methodological processing of the results. Over the period from 2007 to 2011, more than 130 ship hulls that were made from composite materials were inspected using the methods of nondestructive testing.

Before starting a complex of flaw-detection procedures, the test object (a ship hull made of composite materials) was positioned on an even site on a keel block or a transporting trailer is an unfastened and stationary state. In this case, access from any side (including the bottom) to any surfaces of the test object should be provided (except the zone of the shell contact with keel blocks or trailer lodgements). The underwater part of the hull should be carefully cleaned of the layer of dirt up to the surface of the decorative layer or the painted surface (if the hull is painted). The harbor case from the test object should be dismounted.

The primary operation that precedes instrumental nondestructive testing is visual examination of the test object (ship hull). This is aimed at determination of the position of the current ship waterline, revealing outer flaws in the decorative layer, damage to separate elements of the hull structures, and traces of osmotic changes in the surface layers of the hull. Nondestructive testing is performed for 100% of the area of the ship hull surface in the vicinity of the variable waterline, bottom connection lines, side shell plating, and the transom. In addition, 100% of the area of the locations where the bases of the main propulsion engines and longitudinal and transverse components contact the outer shell are tested; the zones of the positioning and fixing of propulsive-steering complexes, the positions of deadwoods and maneuvering propulsion devices, and cuts in the freeboard also undergo inspection. Nondestructive testing is also performed for 100% of the area of the surfaces that are characterized by osmotic changes and zones of emergency contacts of the outer shell on the ship hull. The testing is accomplished with unidirectional access.

In addition, nondestructive testing is performed for 30% of the remaining surface of the underwater hull section and 10% of the area of the surfaces of the freeboard, decks, walls and the roof of the erection. The testing is also performed with unidirectional access. Other braces and surfaces of the ship hull that are made of composite materials are subjected to nondestructive testing if it is necessary and possible. According to the normative documents, the step of the structural nondestructive testing should not exceed 500 mm; at contact points, 250 mm. According to the normative documents, the recorded results of nondestructive testing should contain the data on the area of the flaws and coordinates of their positions. The minimum area of a flaw that is detected in ship-hull structures that are made from composite materials is 4 mm^2. An exact scheme of the flaw positions on a ship hull that is made of composite materials is drawn.

When nondestructive testing was performed for the composite hulls of the ships that are operated under the engineering supervision of the Moscow Branch of the Russian River Register in 2007–2011, the braces of the first group (the outer shell and deck plating) were predominantly inspected. Other braces of the hull are covered, as a rule, by the elements of the shell and rigging, which cannot be easily removed for the nondestructive testing period and thus are difficult (or impossible) to access. However, the data that were obtained as the result of the nondestructive testing of the braces of the first group are sufficient for an objective evaluation of the technical state of ship hull that is made of composite materials upon operation.

The method for determining the technical state of a ship hull that is made of composite materials, which is based on the results of nondestructive testing that is performed using acoustic methods and is aimed at detection of the inner flaws, measurement of their area, and comparison of the results with the maximum admissible value, is protected by RF patent no. 2354964.

The data on the dynamics of operational flaw development that were obtained based on the nondestructive testing of ship hulls made of composite materials by following this technique allows a number of new theories and strength criteria for ship hull structures made from composite materials. These theories are based on the concept of damage accumulation in the process of operation. This allows one to forecast changes in the operational strength of ship hulls that are made of composite materials during their entire lifetime and draw conclusions concerning the durability of a ship hull structure that is made from composite materials as a whole [6–9, 11].

REFERENCES

1 1 1. Ermolov, I.N. and Ermolov, M.I., *Ul'trazvukovoi kontrol. Uchebnik dlya spetsialistov 1 i 2 urovnei kvalifikatsii* (Ultrasonic Testing. Textbook for Specialists of the 1st and 2nd Qualification Levels), Moscow: NPO TsNIITMASh, 1993.

2 2. Gershberg, M.V., Ilyushin, S.V., and Smirnov, V.I., *Nerazrushayushchie metody kontrolya sudostroitel'nykh stekloplastikov* (Methods of Nondestructive Testing for Ship Fiberglass Plastics), Leningrad: Sudostroenie, 1971.

3 3. Lange, Yu.V., *Akusticheskie nizkochastotnye metody nerazrushayushchego kontrolya mnogosloinykh konstruktsii iz kompozitnykh materialov* (Acoustic Low Frequency Methods of Nondestructive Testing of Multilayer Structures from Composite Materials), Moscow: Mashinostroenie, 1991.

3 4. Lange, Yu.V., et al., New Low Frequency Acoustic Flaw Detectors for Nondestructive Testing of Multilayer Structures, *V Mire Nerazrushayushchego Kontrolya*, 2004, no. 3, pp. 12–13.

5. *OST* (Branch Standard) *5.9102-87: Structural Fiberglass Plastics for Shipbuilding*, 1987.

6. Frantsev, M.E., Design Evaluation of Operational Loads and Durability Characteristics of Ship Hulls from Composite Materials, *Morsk. Vestn.*, 2008, no. 4(28), pp. 93–98.

7. Frantsev, M.E., Design Recommendations on Determining the Most Loaded and Vulnerable Elements of a Ship Hull from Composite Materials, *Konstr. Kompoz. Mater.*, 2011, no. 3, pp. 86–97.

8. Frantsev, M.E., The Method for Evaluating a Technical State of a Ship Hull from Composite Materials in the Process of Operation, *Kontrol. Diagn.*, 2009, no. 11, pp. 61–68.

9. Frantsev, M.E., Substantiation of Design Criteria of Operational Strength and Durability of Composite Motor Boats, *Sb. dokl. Mezhdunarodnogo seminara "Suda budushchego" Sektsii "Proektirovanie sudov" Tsentral'nogo Pravleniya NTO sudostroitelei im. akad. A.N. Krylova* (Proc. Int. Seminar "Vessels of the Future"; "Ship Designing" Section of the Central Executive Committee of the Krylov Scientific-Engineering Society of Shipbuilders), St. Petersburg, 2007, pp. 86–91.

10. Frantsev, M.E., Operational Flaws in Hulls of Fiberglass Plastic Vessels, *Katera Yakhty,* 2008, no. 2(212), pp. 90–93; 2008, no. 3(213), pp. 102–105.

11. Frantsev, M.E., The Mode Used for the Estimation of the Technical Condition for the Boat Hull from Composite Materials for Exploitation, *10-th European Conference on Non-Destructive Testing*, Moscow, 2010, part 2, p. 64.

SPELL: 1. Ermolov, 2. Ilyushin, 3. Lange