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APPROXIMATE ESTIMATION OF PROPULSION FOR HIGH-SPEED DISPLACEMENT VESSELS

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Summary
The classification of the main ship modes of the movement, from the point of view of international documents and the principles of the classical theory of ship design, is described in this article. A comparison is made of the requirements for the term "high-speed vessel", from the point of view of the SOLAS convention, and the provisions of the design theory regarding the speed mode of the vessel. Various methods for classifying the types of vessel movement are described, using relative speed and depending on the type of forces applied to the hull of a high-speed vessel. For further research, a transitional mode of motion was chosen, namely the first half of the range of relative velocities from від $F_{r_V} = 1$ *to* $F_{r_V} = 2$*. A schematic description of the main components of the resistance of the environment to the movement of the ship is presented. An assumption is made about the quantitative composition of the types of water resistance for ships of the transitional mode of motion. When calculating the water resistance, the change in the area of the wetted surface of the vessel is taken into account when moving at a high relative speed. An analysis of various forms of ship hull contours for different speeds has been carried out. Based on the experience of shipbuilders, a drawing is proposed showing the effectiveness of using various forms of frames, depending on the relative speed. Using the method least squares, a formula was derived to estimate the residuary resistance of ships moving at a relative speed від* $F_{r_V} = 1$*.The formula is based on a wealth of experience gained in various test tanks. A comparison of the test results of two yacht models with water resistance values obtained using several calculation schemes is proposed in this paper. The test results of the models of the two yachts were compared with the results of statistical calculations and with the results of calculations according to the scheme, using specific data from the experimental pool. The calculation of the power of the main engines of high-speed vessels was carried out, followed by a comparison of the calculated and real values. As an example, the calculation of the power of the main engines for several high-speed ferries was carried out.*

Key words: *propulsion, transitional mode, resistance of water.*

ПРИБЛИЗНА ОЦІНКА ХОДОВОСТІ ВИСОКОШВИДКІСНИХ ВОДОТОНАЖНИХ СУДЕН

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Анотація
У статті описано класифікацію основних режимів руху суден з погляду міжнародних документів та принципів класичної теорії проектування. Зроблене порівняння вимог до терміну «швидкісне судно», з точку зору міжнародної конвенції СОЛАС, і положень теорії проектування стосовно швидкісних режимів руху судна. Описані різні способи класифікації типів руху плавзасобів за відносною швидкістю та залежно від виду сил, прикладених до корпусу швидкохідного судна. Для подальшого дослідження обрано перехідний режим руху, а саме першу половину діапазону відносних швидкостей від $F_{r_V} = 1$ *до* $F_{r_V} = 2$*. Наведено схематичний опис основних складових опору середовища руху судна. Зроблено припущення про кількісний склад видів опору води для перехідного режиму руху. При розрахунках опору води врахована зміна площі змоченої поверхні судна, при русі з великою відносною швидкістю. Проведено аналіз різних форм обводів корпусу для різних швидкостей. На основі досвіду суднобудівників пропонується рисунок, що показує ефективність використання різних форм шпангоутів залежно від відносної швидкості. Методом найменших квадратів виведено формулу з метою оцінки залишкового опору суден, з відносною швидкістю* $F_{r_V} = 1$*. Формула заснована на багатому досвіді, отриманому у різних дослідних басейнах. У роботі пропонується порівняння результатів випробувань двох моделей яхт із значеннями опору води, отриманими з використанням кількох розрахункових схем. Результати випробувань моделей двох яхт порівнювалися з результатами статистичних розрахунків та результатами розрахунків за схемою з використанням конкретних даних дослідного басейну. Проведено розрахунок потужності двигунів швидкохідних суден з подальшим порівнянням розрахункових та реальних значень. Як приклад проведено розрахунок потужності двигунів для кількох швидкісних поромів.*

Ключові слова: *ходкість, перехідний режим, супротив води.*

Introduction. Preliminary calculation of the water resistance to the movement of the vessel, at the first stages of the project, is extremely important, as it is associated with further improvement of the shape of the ship's contours, assessment of the weight load, layout of the premises. Currently, there are many programs for this type of calculation. These programs are based on model test data in towing tanks, data on real ships, approximate formulas, such as the Admiralty formula. If it is possible to compare several types of calculations, then there are additional opportunities for analysis. The formulas obtained using statistical analysis, based on data from a large number of tests in the towing tanks, take into account many parameters of ship hulls: relative length, block coefficient, the ratio of the vessel's width to its draft, and much more. It becomes possible to compare the calculation results using a statistical formula and real data obtained in the towing tanks for a real ship. Calculations of water resistance for ships of the transitional mode of motion are specific. When moving at relative speeds of this mode, the trim appears the area of the wetted surface changes. The choice of the type of propulsion is also related to the expected speed of operation of the vessel and, as a result, the required power of the main engine. The purpose of this article is to compare different variants for calculating the resistance of water to the movement of vessels in a transitional mode.

The various modes of movement of the vessel. The title of this article requires a more detailed analysis of the terms “high-speed” and “displacement”. For an approximate evaluation of the various modes of movement of the vessel, the Froude number based on volume $F_{r_V} = \frac{v}{\sqrt{g^3\sqrt{V}}}$ usually are used.

Three modes are distinguished in the theory of ship design. These modes are determined by the nature forces maintain. If the weight of the vessel Δ is completely balanced by the hydrostatic force, this mode is called displacement $\Delta = \gamma V$, $F_{r_V} < 1$ With further increase of the speed of the vessel the bow rises, the bottom of the vessel will be moved with angle of attack to the surface of the water. Additional force directed perpendicular to the bottom of the vessel arises. This force can be decomposed into two components: hydrodynamic resistance of water and the hydrodynamic lift force *Y*. The transitional mode begins. The weight of the ship is balanced by two forces: the hydrostatic and hydrodynamic $\Delta = \gamma V_1 + Y$, $1 < F_{r_V} < 3$. The hydrostatic force γV_1 is created by the submerged in the liquid part of the body of craft V_1 . The transitional mode has been little studied, because the elements of displacement and planing are parts of the forces. Another difficulty for the study is a variable position of the vessel relative to the water at various speeds. A further increasing of speed leads to a further growth of hydrodynamic force, emersion of vessel and accordingly reducing of the hydrostatic force. The “planing mode” is the regime when hydrodynamic lift forces Y fully support the weight of the craft $\Delta = Y$, $F_{r_V} < 3$.

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International Code of Safety for High-Speed Craft [1], and some national rules [2] give another definition of modes.

"Displacement mode" means the regime, whether at rest or in motion, where the weight of the craft is fully or predominantly supported by hydrostatic forces.

"Non-displacement mode" means the normal operational regime of a craft when non-hydrostatic forces substantially or predominantly support the weight of the craft.

"Transitional mode" means the regime between displacement and non-displacement modes.

For simplicity, the first half of the transition regime, $1 < F_{r_V} < 2$, is classified as a displacement mode, and it can be assumed that the hydrostatic forces predominantly or fully support the weight of the vessel. This separation allows further facilitate the solution of problems of designing ships.

The Registro Italiano Navale [3] defines ship as speed if its velocity m/s $v_{max} \geq 3,7V^{0,1667}$, where V is displacement volume.

Mode of the movement of the vessel is characterized by the Froude number based on volume $F_{r_V} = \frac{v}{\sqrt{g\sqrt[3]{V}}} \to v = 3,13 F_{r_V} V^{0,1667}$. The value $F_{r_V} = \frac{v}{\sqrt{g\sqrt[3]{V}}}$ is obtained by equating the right sides of these two equations. Hence, the vessel can be regarded as high when $F_{r_V} = \frac{v}{\sqrt{g\sqrt[3]{V}}} \geq 1,18$.

Total resistance and its components. In the design of the ship surface of the speed vessels, the optimal ratio of the main dimensions and the coefficients of the hull should be carefully selected. These options have a paramount influence on the propulsion of the vessel, its stability and displacement. The issue is particularly relevant for transitional mode boats, because in these conditions the resistance of the water increases.

The residuary resistance plays a major role in the total resistance by increasing the wavemaking component. Such parameters as the form of contours, relative length, bottom deadrise angle, narrowing of the aft, need attention.

Total resistance and its parts are shown on the Fig. 1.

The experimental experience. Regarding resistance of high-speed vessels, large experimental experience exists.

In the transitional mode, at low values of the load coefficient $c_D = \frac{\Delta}{\gamma B^3}$, V-shaped forms and combined (mixed) forms are preferred. At low speeds V-shaped forms yield combined. The recommendations for the using U-shaped and V-shaped forms are offered, Figure 2 [4]. In the same paper noted that at the beginning of the transitional mode, the option with combined forms: "hard" chine at aft and "soft" chine at the bow are preferred. It is necessary to clarify that in this mode, hydrodynamic lift force appears and therefore it is necessary to design the flat portions of the bottom at the stern, for its effective use.

Among the works that have been devoted to the transitional mode, are the following below.

In 1963, Beys published a study of a series of geometrically similar models with relative length $\frac{L}{B} = 2{,}5 - 6{,}0$, Dandson Laboratory of the Stevens Institute of Technology.

Lindgren, Williams presented results of the research of the series of 9 models of high-speed round bilge displacement vessels in the Swedish State Shipbuilding Tank (SSPA). Length displacement ratio was assumed to be $\frac{L}{\nabla^{\frac{1}{3}}}$ 6, 7 and 8; relative width $\frac{B}{d}$ = 3.0, 3.5 and 4.0. Block coefficient was assumed constant c_b = 0.4 for all models, and the relative length $\frac{L}{B}$ ranged from 4.6 to 8.2. Speed range of Froude number was F_n = 0.4-1.2.

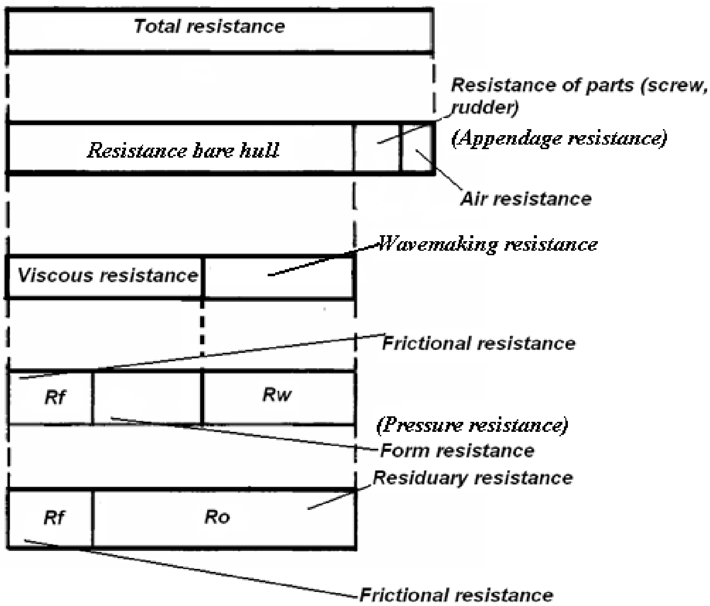

Fig. 1. Total resistance and its components

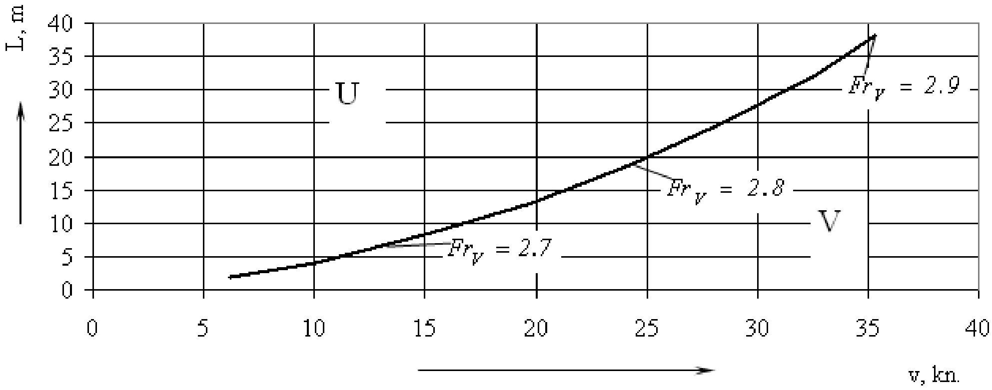

Fig. 2. Application of frames with different shapes at different relative speeds

A very useful work Marwood and Bailey was published in 1976. They conducted tests in the British National Physical Laboratory in relation to a systematic series of 22 models varying relationships $\frac{L}{B}$ and $\frac{B}{d}$, while maintaining constant c_b = 0.397 and c_p = 0.693. The speed changes in the number range F_{r_l} = 0.3-1.2.

Brown diagrams are used to determine the residuary resistance of vessels with $\frac{L}{B}$ = 3,5-7,4, $\frac{B}{d}$ = 3,1-4,4, c_b = 0,29-0,54 at the end of the displacement mode and transitional mode. The data cover ships with the U- and V-shaped contours.

Volodin diagram is built on the basis of large experimental data and help to determine the residuary resistance for round bilge speedboats depending on the length displacement ratio for different number F_{r_V} . The calculation of the frictional resistance produced by the wetted surface of the body corresponding to the static position of the ship.

Nordstrom series of tests is made on the basis of 14 round bilge models, the characteristics of which were as follows: $\frac{L}{B}$ = 4,83-6,94, $\frac{B}{d}$ = 3,16-3,57, c_b = 0,373-0,410, c_p = 0,576-0,599, x_c = -1,79-2,88%, $\frac{\Omega}{\sqrt{VL}}$ = 2,67-2,7, half angle of entrance i_E = 15,1-22,5°.

The systematic Groot series published in 1951, according to test 31 models of high-speed round bilge boats. The geometrical characteristics of hulls are as follows: $\frac{L}{B}$=3,53-10,09, $\frac{B}{d}$=2,72-6,58, c_b=0,293-0,560, c_p=0,463-0,791, x_c=-11,5-3,09%, $\frac{\Omega}{\sqrt{VL}}$= 2,75. Materials widely used at present in the development of forms of speedboats.

Series 64 – test of 27 models of high-speed round bilge boats in Taylor towing tank, 1965. During the tests, the relative length, the beam draft ratio, the block coefficient varied. Models have $\frac{L}{B} = 8,454 - 18,264,$ $\frac{B}{d}$ = 2-4, c_b = 0,35-0,55, c_p = 0,63, $\frac{\Omega}{\sqrt{VL}}$ = 2,6-3,0, i_E = 3,7-7,8°.

The estimation of propulsion. The data have been obtained from various sources (Brown, Volodin, Nordstrom, Groot, SSPA and NPL), were analyzed to estimate the approximate value $\frac{R}{\Delta}$ and its dependence on the parameters of transitional regime vessels. A series of tests included a large range of values $\frac{L}{B}$, $\frac{B}{d}$, c_b,c_p , and various forms of hull, with the U- and V-shaped contours, vary the half angle of entrance [5]. Results of the study based on the relative residuary resistance $\frac{R_o}{\Delta}$ and values $l = \frac{L}{\sqrt[3]{V}}$ shown on

Figure 3 [6]. The residuary resistance is quite a large part, on the average, about 70% of the total resistance in the transitional mode.

Using the method least squares, Formula (1) was obtained. This formula allows us to estimate relative resistance at a relative speed $F_{r_V} = 1$.

$$\left(\frac{R_o}{\Delta}\right)_1 = 4,89\left(\frac{L}{\sqrt[3]{V}}\right)^{-2,96} \quad (1)$$

Evaluation of water resistance R, in the design of high-speed vessel is very important because it is directly linked with the choice of main engine power $N = \frac{R_v}{\eta_S \eta_G \eta \eta_H} = \frac{R_v}{\eta_P}$, where v – speed of the vessel, η – efficiency propeller, open water; η_G – efficiency, gearing; η_H – efficiency, hull; η_S – efficiency, shafting; η_P – efficiency, propulsive.

The value η_P is maximized rational choice of the type of propulsion, depending on the given design speed. Figure 4, average data of [7] is shown. At speeds less than 40 knots, the use of a propeller is possible for more high-speed vessels fully cavitating propeller is preferred. Some ships equipped a combination of the jet propulsion and propeller («Isola di Stromboli»). This option gives opportunity to vary the speed of quality in the operation of the vessel.

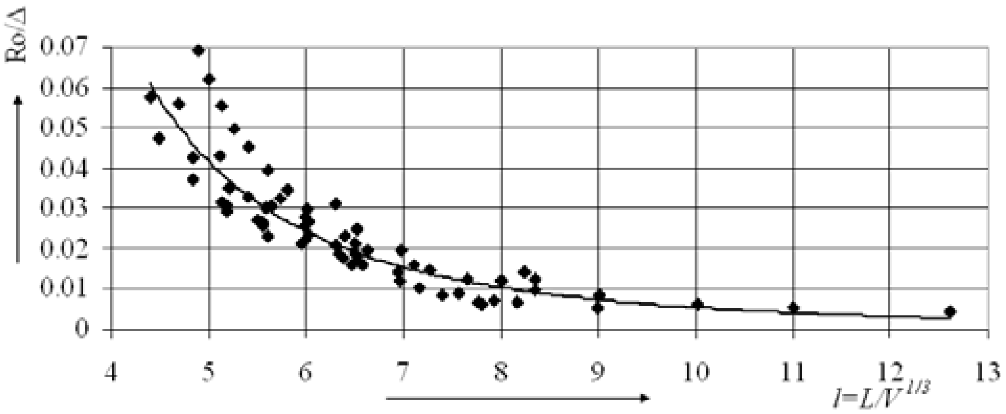

Fig. 3. Relative residuary resistance $\frac{R_o}{\Delta}$ *on* $l = \frac{L}{\sqrt[3]{V}}$ *, at* $F_{r_V} = 1$

The most common method of calculation – a breakdown of the total resistance RT into two components: the frictional resistance $R_f = \zeta_F \frac{\rho v^2}{2} \Omega$ (ζ_F – frictional resistance coefficient of a body, ρ – the density of water) and residuary resistance Ro.

Changes in average draft, while moving in the transitional regime, entails a change in the wetted surface area ρ. This change can be taken into account by using the Bunkov researching [8]. The study involved a test series of 37 models of high-speed monohull vessels with "hard" chine and combined (mixed) forms and transom stern. During the tests the relative centre of gravity (measured from transom) and the load coefficient of models $c_D = \frac{\Delta}{\gamma B^3}$ varied.

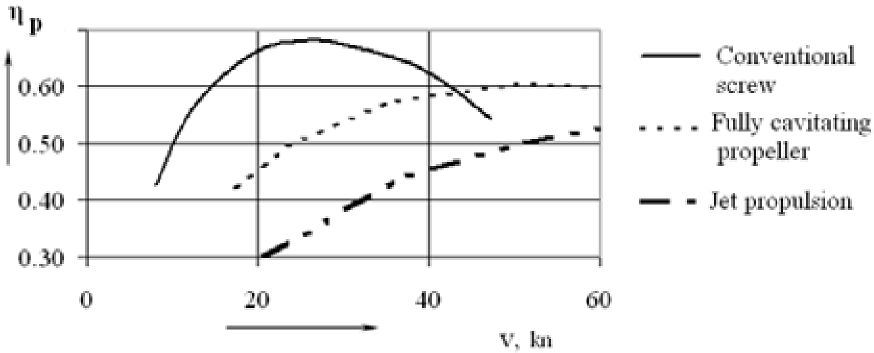

Fig. 4. Efficiency propulsive values for different types of propulsion

The following calculation scheme is possible: $F_{r_V} \to l = \frac{L}{\sqrt[3]{\nabla}} \to R_o$ – residuary resistance $\to$ ζf – frictional resistance coefficient of a body with considering roughness allowance $\to \Omega$ – wetted surface area, Bunkov test results $\to R_f = \zeta_f \frac{\rho v^2}{2} \Omega$ – frictional resistance $\to R_T = R_o + R_f$.

For definition of frictional resistance coefficient ζf is possible after calculation Reynolds number, $R_e = \frac{L_v}{\gamma}$, where $\gamma = 1,2 \times 10^{-6} m^2 / sek$ – viscosity of water.

Air resistance is determined by the expression $R_a = 0,5c\rho_a (v \pm v_w)^2 S_a$. In this formula c – air resistance coefficient, for high-speed vessels – 0,4-0,6; $\rho_a = 1,226 \cdot kg / m^3$ – density of air; v – vessel speed; v_w – the projection of the wind speed in the direction of movement of the vessel, m/s (the plus sign to the headwind, the minus sign – for passing); S_a – area exposed to wind, m^2.

The value of air resistance, for example, for ship «Volcan de Tauro» is 3% of the bare hull resistance. With greater accuracy air resistance is determined using the results of wind tunnel models.

To check the effectiveness of method, test calculations were carried out, Table 1. The information about the movement of the ferry "Guizzo" against the wave is in the article [9].

Table 1

Power of engine of high-speed monohull ferry

Name ship	Speed, kn.	Power of engine, mWt		Error, %
		real	calculation	
Guizzo	40	28.0	28.0	0
Albayzin	40	21.6	21.0	2.8
Isola di Capri	29	9.4	10.0	2.8
Pegasus One	36	24.0	29.0	17

In table 2, the main dimensions of two yachts are recorded. The general arrangement of one of these yachts is shown in Figure 5. Models of these vessels were tested in the Vienna Model Basin. The first of these yachts belongs to the class of high-speed vessels; the relative speed of the vessel is $F_{r_V} = 1,2$. The second ship has a relative speed of $F_{r_V} = 1$ which is typical for the beginning of the transitional mode of motion.

For more information on the designation of the navigation area for these yachts, see the article [10].

Table 2

Main dimensions of two yachts

Length L_{pp}, m	Width B, m	Draft d, m	Displacement, t	Speed v, kn	Power of main engines, kW
34	7.48	2.57	310.1	16	2 x 1000
48	10.09	2.68	590	16.5	2 x 1200

In order to compare the results of calculations: tests of models in the towing tank, calculations made according to the scheme described above and calculations using formula (1), Figure 6 was constructed. It can be seen from the graph that the calculations made using the scheme and the test results in the towing tank are practically the same. The results of calculations by formula (1) differ from the test results by 15%.

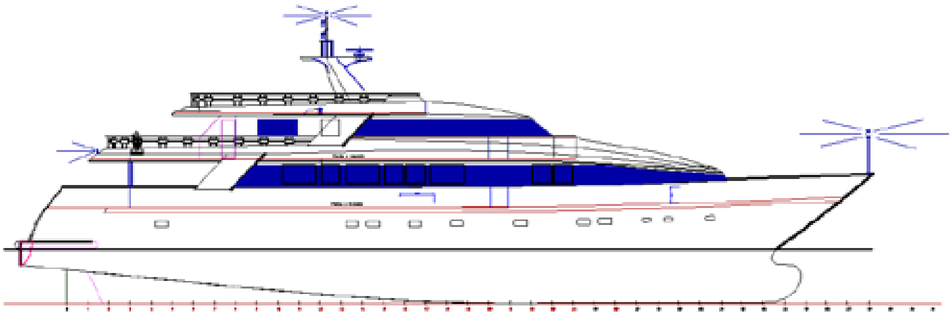

Fig. 5. Part of the general arrangement of Yacht (length 34 m)

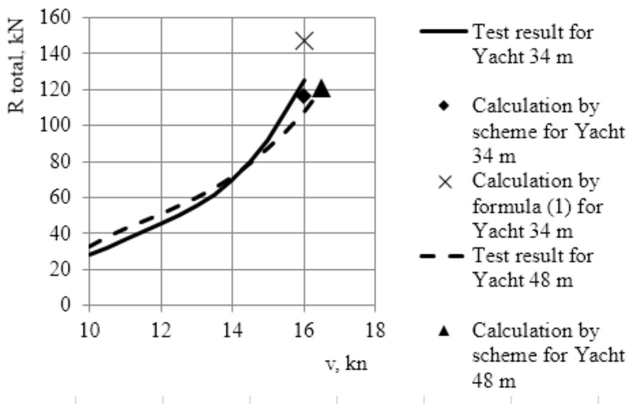

Fig. 6. Results of tests and calculations according to the scheme and formula (1)

Conclusions. As a result of calculating the water resistance according to the scheme and using the formula $\left(\frac{R_o}{\Delta}\right)_1 = 4,89\left(\frac{L}{\sqrt[3]{V}}\right)^{-2,96}$, results were obtained that make it possible to evaluate the accuracy of these methods. The error in applying both methods can range from 0 to 17%. When applying the calculations by scheme, it is necessary to carefully choose the graph for calculating the residuary resistance. The parameters of the models, on the basis of the tests of which such a graph is built, should correspond as much as possible to the parameters of a real vessel.

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