Oleksii P. Yastreba
Ястреба Алексей Петрович

УДК 629.5.01

METHOD FOR DETERMINATION OF ESCORT TUGS MAIN DIMENSIONS AND CHARACTERISTICS AT CONCEPTUAL DESIGN STAGE

МЕТОД ОПРЕДЕЛЕНИЯ ГЛАВНЫХ РАЗМЕРЕНИЙ И ХАРАКТЕРИСТИК ЭСКОРТНЫХ БУКСИРОВ ПРИ КОНЦЕПТУАЛЬНОМ ПРОЕКТИРОВАНИИ ЭТИХ СУДОВ

DOI 10.15589/SMI20180203

Oleksii P. Yastreba А. П. Ястреба, старш. преп.
oleksii.yastreba@nuos.edu.ua
ORCID: 0000-0002-5505-1281

Admiral Makarov National University of Shipbuilding, Mykolaiv
Национальный университет кораблестроения имени адмирала Макарова, г. Николаев

Abstract. The paper is devoted to the development of a method for determination of main dimensions and characteristics of escort tugs designed for escorting tankers, gas carriers and other types of vessels with hazardous cargoes. Classification Societies require a reasonable preliminary calculation of the maximum holding force acting on a tug at the escort speed of 8 and 10 knots to be submitted in order to assign an escort class to a tug. The method for determination of hydrodynamic forces acting on the ASD escort tug during stationary escort operations is described. The method is based on processing of the data collected during towing tests of such tugs in the towing tank of the National University of Shipbuilding (NUOS). Processing of the experimental data allowed to obtain regression dependencies for stationary hydrodynamic forces acting on the escort tug on the drift angle ranging from 0 to 90 degrees. Towing tests were carried out on request of design organizations, and escort tug projects by TransShip Corporation were mainly used. These projects are TUG40, TUG50, TUG55, TUG55TA, TUG60, TUG60L, TUG60LA and TUG70 by E. D. Demidov, General Designer. The data obtained based on using the developed dependencies was compared with the data of full-scale tests of escort tugs of this series. Obtained dependences are included in the equations of motion of escort tug operational purpose, which is an integral part of the optimization problem of determination of escort tug main dimensions and characteristics. A method for solving the transcendental equations of the tug stationary motion during escort operations is proposed, similar to the method for solving an optimization problem. Using the obtained method for determination of hydrodynamic forces and the operational purpose, the problem of determination of escort tug main dimensions is defined with solution oriented to optimize dimensions based on escort tug serving a random stream of vessels arriving at the seaport.

Keywords: escort; towing tank; towing tests.

Анотація. Розроблені метод визначення головних розмірів та характеристики ескортних буксирів, призначених для супроводження танкерів, газовозів та інших типів суден, які перевозять небезпечні вантажі. За вимогами класифікаційних товариств для надання буксиру ескортного класу необхідно здійснити попередній розрахунок максимального утримувального зусилля буксира при швидкості ескортування 8 та 10 вузлів. Викладено метод визначення гідродинамічних сил, які діють на корпус ескортного буксира в умовах стаціонарних ескортних операцій. Метод побудовано на основі обробки даних буксирувальних випробувань цих буксирів у дослідному басейні Національного університету кораблебудування (НУК). Обробка даних буксирувальних досліджень дозволила побудувати регресійні залежності для стаціонарних гідродинамічних сил, які діють на буксир у діапазоні кутів дрейфу від 0 до 90 градусів. Буксирувальні випробування були проведені на замовлення проектних організацій, більша кількість яких виконано за проектами ескортних буксирів корпорації TransShip. Це проекти буксирів TUG40, TUG50, TUG55, TUG55TA, TUG60, TUG60L, TUG60LA і TUG70 генерального конструктора Є.Д. Дємідова. Виконано порівняння результатів, отриманих на основі використання побудованих залежностей, з результатами натурних випробувань ескортних буксирів цієї серії. Отримані залежності включені в рівняння руху задачі функціонування ескортного буксира, яка є невід'ємною частиною оптимізаційної задачі визначення головних розмірів та характеристик ескортного буксира. Був запропонований метод розв'язання трансцендентних рівнянь стаціонарного руху буксира в умовах ескортних операцій, аналогічний методу розв'язання оптимізаційної задачі. За допомогою побудованого методу визначення гідродинамічних сил та задачі функціонування сформовано задачу визначення головних

розмірів буксира з орієнтуванням її розв'язання на оптимізацію розмірів на основі обслуговування ескортним буксиром випадкового потоку суден, які відвідують морський порт.

Ключові слова: ескортування; дослідний басейн; буксирувальні випробування.

Аннотация. Разработаны метод определения главных размерений и характеристики эскортных буксиров, предназначенных для сопровождения танкеров, газовозов и других типов судов, которые перевозят опасные грузы. По требованиям классификационных обществ для присвоения буксиру эскортного класса необходимо осуществить обоснованный предварительный расчет максимальной удерживающей силы буксира при скорости эскортирования 8 и 10 узлов. Изложен метод определения гидродинамических сил, действующих на эскортный буксир типа ASD в условиях стационарных эскортных операций. Метод построен на основе обработки данных буксировочных испытаний таких буксиров в опытовом бассейне Национального университета кораблестроения (НУК). Обработка данных экспериментальных исследований позволила построить регрессионные зависимости для стационарных гидродинамических сил, действующих на эскортный буксир в диапазоне углов дрейфа от 0 до 90 градусов. Буксировочные испытания были проведены по заказам проектных организаций, наибольшее число которых осуществлено по проектам эскортных буксиров корпорации TransShip. Это проекты буксиров TUG40, TUG50, TUG55, TUG55TA, TUG60, TUG60L, TUG60LA и TUG70 генерального конструктора Е. Д. Демидова. Выполнено сравнение данных, полученных на основе использования построенных зависимостей, с данными натурных испытаний эскортных буксиров этой серии. Полученные зависимости включены в уравнения движения задачи функционирования эскортного буксира, которая является неотъемлемой частью оптимизационной задачи определения главных размерений и характеристик эскортного буксира. Предложен метод решения трансцендентных уравнений стационарного движения буксира в условиях эскортных операций, аналогичный методу решения оптимизационной задачи. С помощью построенного метода определения гидродинамических сил и задачи функционирования сформирована задача определения главных размерений эскортного буксира с ориентацией ее решения на оптимизацию размерений на основе обслуживания эскортным буксиром случайного потока судов, посещающий морской порт.

Ключевые слова: эскортирование; опытовый бассейн; буксировочные испытания.

References

[1] Azimuth Stern Drive Tug [Electronic resourse] / Damen Shipyards. – Available at : https://products.damen.com.

[2] Slizhevskiy N. B. *Raschet eskortnykh kharakteristik buksira* [Calculation of escort characteristics of the tug] / N. B. Slizhevskiy, A. S. Markov // *Zbirnik naukovikh prats UDMTU*. – 2002 – № 7 (385). – S. 3–12.

[3] Pozdeev V. A. *Metod opredeleniya gidrodinamicheskikh sil, deystvuyushchikh na buksir v rezhimakh eskortnykh operatsiy* [Method for determination of the hydrodynamic forces acting on the tow modes escort operations] / V. A. Nekrasov, A. P. Yastreba // *Zbirnik naukovikh prats NUK*. – 2010. – № 6. – S. 47–55.

[4] *Razrabotka programmnogo obespecheniya dlya opredeleniya maksimalnoy uderzhivayushchey sily i ugla krena eskortnykh buksirov v sootvetstvii s trebovaniyami Pravil RS* [Development of software for determining the maximum holding force and roll angle of escort tugboats in accordance with the requirements of the RS Rules] / A. I. Nemzer, A. V. Yurkanskiy, M. A. Kuteynikov, M. Ye. Zakharov // *Nauchno-tekhnicheskiy sbornik Rossiyskogo morskogo registra sudokhodstva*. – 2016. – № 42/43. – S. 70 –74.

[5] Voytkunskiy Ya. I. *Spravochnik po teorii korablya t.3. Upravlyaemost vodoizmeshchayushchikh sudov* [Handbook of the theory of the ship v.3. Handling of displacement vessels] / Ya. I. Voytkunskiy. – L.: Sudostroenie, 1985. – 544 s.

[6] *Oborudovanie dlya eksperimentalnogo opredeleniya kharakteristik eskortnykh buksirov i metodika perescheta rezultatov modelnykh ispytaniy na naturu* [Equipment for the experimental determination of the characteristics of escort tugboats and methods for recalculating the results of model tests for nature] / V. A. Nekrasov, D. A. Drobot, S.A. Cherevatenko, A. P. Yastreba // *Innovatsiï v sudnobuduvanni ta okeanotekhnitsi (5.10–7.10.2011): Materiali II mizhnarodnoï naukovo-tekhnichnoï konferentsiï prisvyachenoï 20-richchyu nezalezhnosti Ukraïni* / Natsionalniy universitet korablebuduvannya imeni admirala Makarova. – M. : NUK, 2011. – S. 88–90.

[7] Nekrasov V. A. *Opredelenie kharakteristik eskortnykh buksirov na osnove dannykh modelnykh ispytaniy v opytovom baseyne NUK* [Characterization of escort tugboats based on data from model tests in the NUOS towing tank] / V. A. Nekrasov, A. P. Yastreba // *Innovatsiï v sudnobuduvanni ta okeanotekhnitsi (4.10–6.10.2012): Materiali III mizhnarodnoï naukovo-tekhnichnoï konferentsiï prisvyachenoï 75-richchyu stvorennya Mikolaïvskoï oblasti* / Natsionalniy universitet korablebuduvannya imeni admirala Makarova. – M. : NUK, 2012. – S. 139–141.

[8] Craneship [Electronic resourse]. – Available at :. www.craneship@.ua.

[9] Ivanov A. *Robot po imeni «Panda»*[Robot named «Panda»] / A. Ivanov // *Sudostroenie i sudoremont.* – 2011. – № 6 (50). – S. 22–29.

[10] Nekrasov V. A. *Formulirovka optimizatsionnoy zadachi vybora glavnykh razmereniy eskortnogo buksira* [The formulation of the optimization problem of the choice of the main dimensions escort tug] / V. A. Nekrasov, A. P. Yas-

treba // *Innovatsiï v sudnobuduvanni ta okeanotekhnitsi (20.05–22.05.2015): Materiali vseukraïnskoï naukovo-tekhnichnoï konferentsiï z mizhnarodnoyu uchastyu «Suchasni tekhnologiï proektuvannya, pobudovi, ekspluatatsiï i remontu suden, morskikh tekhnichnikh zasobiv i inzhenernikh sporud»* / Natsionalniy universitet korablebuduvannya imeni admirala Makarova. – M. : NUK, 2015. – S. 46–47.

[11] IMO. Resolution A. 751(18) [Text], 1993.

[12] Rules for the Classification of Steel Ships [Text] / Bureau Veritas. – Chapter 13, Sec.1, 2, 3. – P. 55–70.

[13] MaxSurf 20 enterprise V8i. Bentley engineering 2013 [Text].

[14] Gofman A. D. *Dvizhitelno-rulevoy kompleks i manevrirovanie sudna* [Propulsion and steering complex and maneuvering vessel]: Spravochnik / A. D. Gofman. – L.: Sudostroenie, 1988. – 360 s.

[15] Khimmelblau D. R. *Prikladnoe nelineynoe programmirovanie* [Applied nonlinear programming]: / D. R. Khimmelblau. – M.: Mir, 1975. – 576 s.

[16] *Tekhnicheskiy otchet o provedenii eskortnykh ispytaniy buksira «Pantera», proekt TUG60L. TUG60L.360285.005*. – Kirgan Holding S.A., 2010. – 9 s.

[17] Nekrasov V. A. *Issledovatelskoe proektirovanie eskortnykh buksirov* [Research design escort tugs] / V. A. Nekrasov, A. V. Bondarenko, A. P. Yastreba // *Innovatsiï v sudnobuduvanni ta okeanotekhnitsi (11.10 – 13.10.2017): Materiali VIII mizhnarodnoï naukovo-tekhnichnoï konferentsiï* / Natsionalniy universitet korablebuduvannya imeni admirala Makarova. – M. : NUK, 2015. – S. 46–47.

Problem statement. Determination of escort tugs main dimensions and characteristics is a recent problem of tug resource supplement of the modern seaports.

The solution to this problem is usually carried out at conceptual design stage (design study). At the same time for the modern seaports the ASD escort tug is the most effective tug class in terms of power and maneuverability [1]. Small size (maximum length up to 35 meters) allows ASD escort tugs to escort tankers, gas carriers, chemical carriers and other types of vessels carrying hazardous cargoes with displacement of 100–120 thousand tons. Classification Societies require calculation of the maximum steering force at the escort speed of 8 and 10 knots to be submitted in order to assign an escort class to a tug. To calculate the steering force and to determine escort tugs main dimensions and characteristics, a method was developed that allows these values to be determined at conceptual design stage.

Latest research and publications analysis. The papers by N. B. Slizhevskiy, A. S. Markov [2] and V. A. Pozdeev, V. A. Nekrasov, A. P. Yastreba [3] are devoted to determination of the forces acting on the ASD escort tugs during stationary escort operations. The effect of unsteady forces on the ASD tug is explored in the paper by A. I. Nemzer, A. V. Yurkanskiy, M. A. Kuteynikov, M. E. Zakharov [4]. In the paper [2], the determination of steady forces is carried out from a perspective of the hydrodynamic vortex theory of the flow of fluids around the bodies. In this paper a tug and a skeg are considered as a whole. In the paper [3], steady forces acting on a tug are determined based on the consideration of the tug hull and its skeg as separate units, followed by using the experimental data on blow-downs of ship-shaped bodies in the wind tunnel, summarized by N. I. Anisimova [5], for these parts of the hull.

Separation of previously unsolved parts of the general problem. The following usage of methods for determination of steady forces acting on a tug during stationary escort operations, described in the papers [2, 3], indicated the possibility of substantial refinement of their values based on experimental data on positional handling characteristics of escort tugs collected during tests in the NUOS towing tank. The tests were carried out using special equipment that was designed, manufactured and used in experimental tests of the forces acting on the escort tug models with direct participation of the author of this article [6, 7].

The most presentable group of escort tugs, undergone the towing tests in the NUOS towing tank, is a range of escort tugs designed by E. D. Demidov, TransShip General Designer. This group includes the following escort tug projects: TUG40, TUG50, TUG55, TUG55TA, TUG60, TUG60L, TUG60LA and TUG70, that present a large part of power and displacement range of escort tugs. These projects are presented on the of CraneShip website [8] and in the “Shipbuilding and Ship Repair” magazine [9].

THE ARTICLE AIM — development of a method for determination of escort tugs main dimensions and characteristics at the conceptual design stage.

To develop this method, a number of objectives were achieved. Received solutions were applied in this paper.

The first objective was to develop a new method for determination of forces acting on a tug during stationary escort operations based on data collected during towing tests of escort tug models of TUG40–TUG70 projects in the NUOS towing tank.

The second objective of the proposed method for determination of the escort tug main dimensions and characteristics was to improve its operational purpose,

consisting in re-orientation of this purpose from a deterministic approach with fixed characteristics of the escorted vessel to the escort tug being able to serve a certain stream of escorted vessels, i.e. consideration of the escorted vessel to be of random displacement value. For the first time such a re-orientation was carried out by the author of this article in the report by V. A. Nekrasov, A. P. Yastreba [10].

Finally, the main goal of design study is to define and solve the optimization problem of determination of tug main elements and characteristics based on the described operational purpose of the escort tug. At the same time the definition of the optimization problem for tug main elements described in the paper [10] requires additional consideration of Classification Societies requirements to safety of escort operations in terms of handling capabilities of the escorted vessel, stipulated due to the escorted vessel limitation in performing zigzag maneuver during escort operation [11].

Methods, object and subject of research. In this study a method was used to determine the forces acting on the tug hull during escort operations, based on processing of the data collected during towing tests of escort tug models in the towing tank; Powell's method — one of the non-linear programming methods was used to find a global minimum in the optimization problem of the objective function. ***The object of the research*** is the design process, ***the subject of the research*** is the method for determination of the escort tug main dimensions and characteristics.

Basic material

1. The method for determination of forces acting on the tug during stationary escort operations

The method is based on the data from a number of ASD escort tug projects, undergone the towing tests in the NUOS towing tank. This range consists of the following escort tugs: TUG40, TUG50, TUG55, TUG-55TA, TUG60, TUG60L, TUG60LA and TUG70, that present a large part of the power and displacement range of the ASD escort tugs, currently used in seaports.

The method is designed to use the obtained expressions for the forces acting on the tug as part of the equations of stationary escort operations represented by Fig. 1 and equalities (1), used in determination of steering force and braking force required for the Classification Society to assign a class [12] to escort tug.

The values of the above characteristics of the stationary movement mode of the escort tug and escorted vessel are determined by solving the following system of equations [10]:

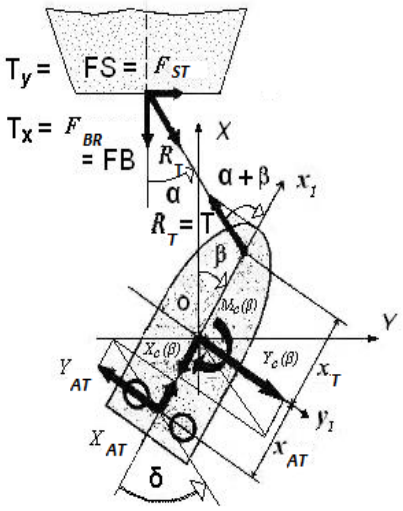

Fig. 1. Chart of escort configuration:

R_T — towline pull; x_T — distance to the bow towing eye; α — towline angle; β — drift angle of the escort tug; δ — tilt angle of the azimuth thrusters; X_c — longitudinal hydrodynamic force acting on the escort tug hull; Y_c — lateral hydrodynamic force; M_c — hydrodynamic momentum; X_{AT} — longitudinal component of the effective pull of two azimuth thrusters, acting on the tug hull as it moves at speed V_s and with angle of inflow to the azimuth thrusters (β – δ) created by this movement; Y_{AT} — lateral component of the effective pull of two azimuth thrusters, acting on the tug hull as it moves at speed V_s and with angle of inflow to the azimuth thrusters (β – δ) created by this movement; x_{AT} — distance to the vertical axes of azimuth thrusters

$$\begin{aligned} &R_T\cos(\beta+\alpha)+X_C(\beta)+X_{AT}(\beta-\delta)=0\\ &-R_T\sin(\beta+\alpha)+Y_T(\beta)+Y_{AT}(\beta-\delta)=0\\ &-R_T\sin(\beta+\alpha)x_T+M_C(\beta)+Y_{AT}(\beta-\delta)x_{AT}=0 \end{aligned} \quad . (1)$$

In this case, the projections of active forces $X_c(\beta)$, $Y_c(\beta)$ and momentum $M_c(\beta)$ on the axes of $ox_1y_1z_1$ coordinate system linked to the tug are determined by the expressions below

$$\begin{aligned} X_C(\beta)&=C_X(\beta)\rho v^2/2A_L\\ Y_C(\beta)&=C_Y(\beta)\rho v^2/2A_L\\ M_C(\beta)&=C_M(\beta)\rho v^2/2A_LL \end{aligned} \quad , \quad (2)$$

where ρ — fluid density; v – tug speed; A_L — lateral underwater area; L — waterline length.

As a result of experimental tests in the NUOS towing tank, it was found that the structural dependence of the coefficients of the active forces $C_X(\beta)$, $C_Y(\beta)$ and momentum $C_M(\beta)$ on the drift angle β ranging from 0 to 90 degrees can be represented by the following approximate expressions:

$$C_X(\beta) = -0{,}075\sin\{[\pi - \arcsin(C_{X0}/0{,}075)][1-\beta/\psi]\}$$
$$C_Y(\beta) = 0{,}5C_{y\beta}\sin 2\beta\cos\beta + c_2\sin\beta|\sin\beta| \quad ,(3)$$
$$C_M(\beta) = C_{m\beta}\sin 2\beta$$

where C_{X0} — drag coefficient of the tug ahead going at speed v; $\psi = \psi_1 + \psi_2$ — trim angle (ψ_1 — static trim and ψ_2 — running trim, determined according to the data [5]); $C_{y\beta}$, c_2, and $C_{m\beta}$ — positional derivatives of the lateral force coefficients and momentum coefficient with respect to drift angle β.

Positional derivatives $C_{y\beta}$, c_2 and $C_{m\beta}$ depend on the geometric characteristics of the hull. When considering the main body of the tug hull and tug skeg as a whole, the following characteristics are selected:

σ_1 — lateral area coefficient;

d/L — ratio of average draft d to waterline length L;

d/B — ratio of average draft d to waterline beam B;

L/B — ratio of waterline length L to waterline beam B;

C_p — prismatic coefficient.

Selection of these characteristics is determined by simplicity of their determination by using Maxsurf program [13] at conceptual and preliminary design stages.

The structural dependence of positional derivatives $C_{y\beta}$, c_2 and $C_{m\beta}$ on the characteristics of the tug hull with the skeg included is adopted by analogy with the structural dependence of the forces and momentum coefficients specified in the vessel handling theory [14]:

$$C_{y\beta} = \pi(d/L)(a_1/C_P)\text{^}(2{,}5)((L/B)/a_2)\text{^}$$
$$\text{^}(0{,}33)+(\sigma_l - a_3)$$
$$c_2 = b_1(3(d/B))\text{^}(0{,}5)(b_2/C_P)\text{^}(1{,}5)+ \quad , \quad (4)$$
$$+b_3(\sigma_l - b_4)$$
$$C_{m\beta} = d_1(d/L)d_2(d_3 - C_P)+(d_4 - \sigma_l)$$

At the same time the processing of the data presented by the above-mentioned range of design solutions for the escort tugs resulted in the following values of the coefficients ai, bi and di (i = 1, 2, 3, 4):

$$a_1 \approx 0{,}720;\ a_2 \approx 2{,}941;\ a_3 \approx 0{,}962;$$
$$b_1 \approx 0{,}722;\ b_2 \approx 0{,}853;\ b_3 \approx 0{,}851;\ b_4 \approx 0{,}953; \quad (5)$$
$$d_1 \approx 0{,}383;\ d_2 \approx 0{,}104;\ d_3 \approx 0{,}602;\ d_4 \approx 0{,}904.$$

The approximation quality of the experimental data on the forces acting on the hull of the TUG60L tug ("Pantera"), obtained by the described method in the absolute OXYZ coordinate system at speed of 6, 8 and 10 knots, is shown on Fig. 2. The Figure is based on experimental data similar to given in the paper [3] for the TUG60 tug project.

The obtained dependences of hydrodynamic forces (2)–(5) were used to solve the transcendental equations of tug motion during stationary escort operation

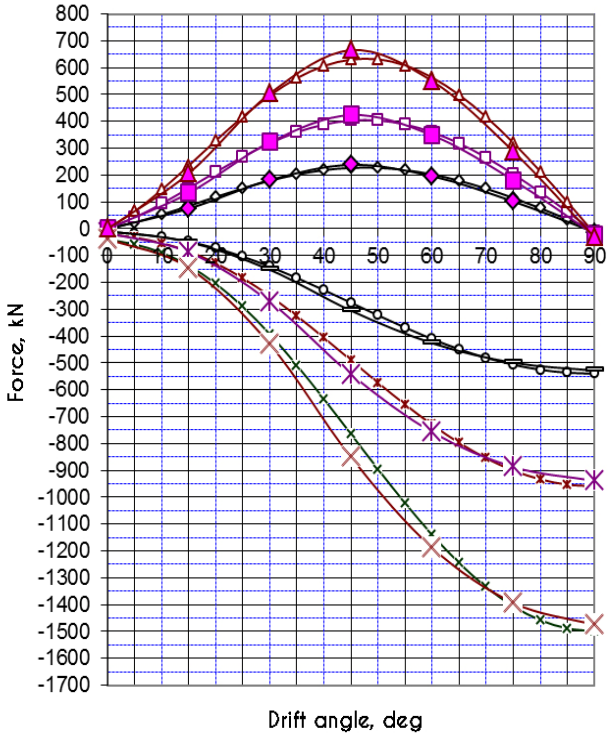

Fig. 2. Dependences of hydrodynamic forces *XX* and *YY* acting on the hull of the TUG60L tug ("Pantera") on the drift angle:
— *XX* V_s = 6 kn; — *YY* V_s = 6 kn;
— *XX* V_s = 8 kn; — *YY* V_s = 8 kn;
— *XX* V_s = 10 kn; — *YY* V_s = 10 kn;
— *XX* V_s = 6 kn, NUOS test; — *YY* V_s = 6 kn, NUOS test; — *XX* V_s = 8 kn, NUOS test; — *YY* V_s = 8 kn, NUOS test; — *XX* V_s = 10 kn, NUOS test; — *YY* V_s = 10 kn, NUOS test

modes (1). With given value of speed v and towline angle α, the solution to these equations of motion is obtained by finding a global minimum (zero) in the unconstrained optimization problem of the following objective function $F(\beta, \delta, R_T)$ of the independent variables β, δ, R_T:

$$F(\beta,\delta,R_T) = (\sum F_x)^2 + (\sum F_y)^2 + (\sum M_z)^2, \quad (6)$$

by one of the methods of nonlinear programming — Powell's method [15]. In the expression for the objective function (6), the components ΣF_x, ΣF_y and ΣM_z are the right sides of the equations (1).

The solutions to the equations of escort operations (1) obtained by the method described were compared with the data of full-scale escort tests of existing tugs.

For the above TUG60L escort tug ("Pantera"), the solutions to the equations of motion (1) with values of the steering force FS, while using the data from the stated experimentally valid method for determination of hydrodynamic forces acting on the tug hull, are shown on the Fig. 3. The results of full-scale tests of the TUG60L tug [16] are shown on the same Figure.

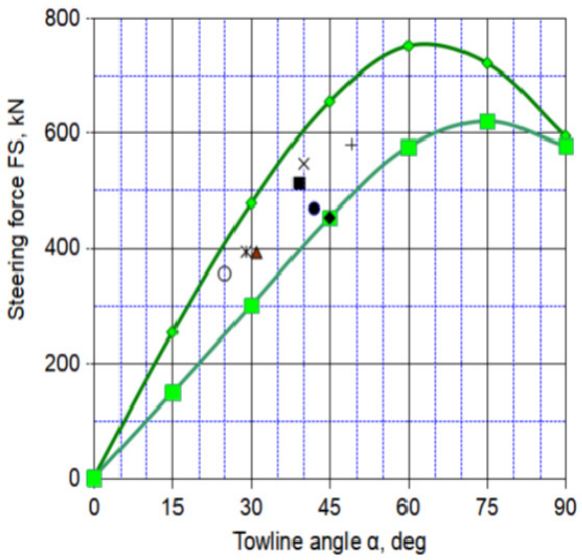

Fig. 3. Dependence of the steering force FS of the TUG60L escort tug ("Pantera") on the towline angle α:
— *FS* V_s = 10 kn; — *FS* V_s = 8 kn, — Escort 1 V_s = 7,9 kn; — Escort 2 V_s = 7,9 kn; — Escort 3 V_s = 7,7 kn; — Escort 4 V_s = 7,8 kn; — Escort 5 V_s = 10 kn; — Escort 6 V_s = 9,1 kn; — Escort 7 V_s = 9,5 kn; — Escort 8 V_s = 9,8 kn

2. Improvement of definition of the escort tug operational purpose

Modern seaport's significant problem of tug resource supplement is to orient the ordered tug towards special group of vessels arriving at the seaport. The reason for this is that vessels with hazardous cargo arriving at seaport are serviced by few escort tugs of different power. Small escort tug is not able to escort large vessels. Meanwhile, using powerful tugs for escorting small vessels is not of economic benefit. Due to the fact that displacement or deadweight of vessels with hazardous cargo arriving at the port are random values, the orientation of the ordered escort tug should be carried out based on the assumption of the displacement or deadweight of the served group of vessels being a random value determined by distribution law based on empirical data. The generation of such random variable is carried out using the Monte-Carlo method.

3. Further development of determination and solving of the optimization problem of selecting the escort tug main elements

In general terms, such escort tug optimization problem is defined and solved in the papers by V.A. Nekrasov, A.V. Bondarenko, A.P. Yastreba [17].

The problem consists in minimization of the objective function (OF)

$$\mathrm{OF}\{U, x\} \Rightarrow \mathrm{extr}$$

subject to the constraints:

$$En(x) \geq 0, \quad n = 1, 2, 3;$$
$$Fk(x) \geq [Fk], \quad k = 1, 2, \ldots, K;$$
$$PCl[Pt] \leq [PCl], \quad l = 1, 2, \ldots, L;$$
$$x \leq xq, \quad q = 1, 2, \ldots, Q,$$

where $En(x) \geq 0$ — constraints providing the necessary level of tug efficiency (constraints on buoyancy, capacity, performance, etc);

$Fk(x) \geq [Fk]$ — reliability constraints — indicators of reliable performance of functional operations related to the implementation of such nautical qualities as stability, unsinkability, strength, handling capabilities and seaworthiness of the tug;

$[Fk]$ — normative values of these indicators, regulated by Classification Societies and standards;

$PCl[Pt] \leq [PCl]$ — functional constraints on design, construction and operation budgets of the tug, as well as reimbursement for damage caused by the tug;

$[PCl]$ — limit values of these budgets;

U — vector of geographical and climatic environment parameters and requirements of the terms of reference;

x — vector of independent variables (of main elements of the tug);

xq — vector of constraints on independent variables.

Solution scheme to this optimization problem at design study stage is shown on Fig. 4.

Author's contribution to development of the optimization method of the escort tug design study, described in the report [17], is:

– development of the stated above method for solving transcendental equations of the escort tug motion;

– inclusion of this method in the process of finding the optimal design solution for the escort tug designed to service defined group of vessels arriving at the seaport;

– consideration of Classification Societies requirements to the safety of escort operations, stipulated due to the limited handling capabilities of the escorted vessels at relatively low speed of escort operations. These requirements, depending on the deadweight and type of the escorted vessel, establish the required steering forces for the escort tug to be not less than the values specified for those two most typical types of escorted vessels at a speed of 10 knots as it is shown on the Fig. 5.

As a result of solving the optimization problem of determination of main dimensions and characteristics of the escort tug serving a random stream of vessels with hazardous cargoes of displacements specified by the distribution shown on the Fig. 6, arriving at the seaport, such as the Yuzhny port, the design of tug was obtained with dimensions and characteristics relatively equal to corresponding values of the above TUG60L tug project ("Pantera").

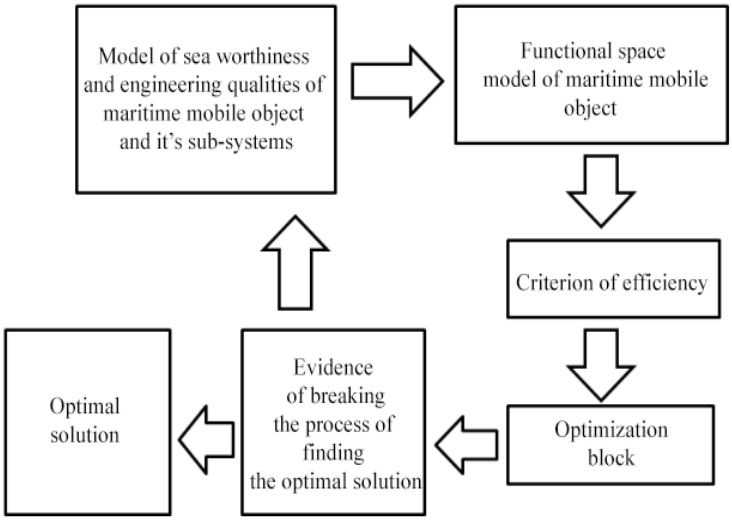

Fig. 4. Block diagram for finding the optimal solution to the problem of the escort tug optimal synthesis for its operation conditions

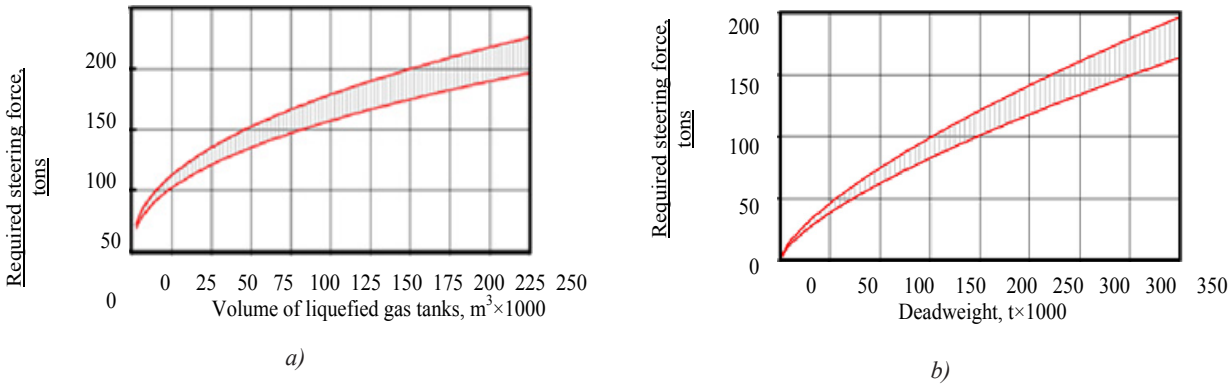

Fig. 5. Example of IMO requirements to the steering force of the escort tug, tons, depending on the deadweight of the escorted vessel, tons:

a — dependence for gas carriers; *b* — dependence for tankers

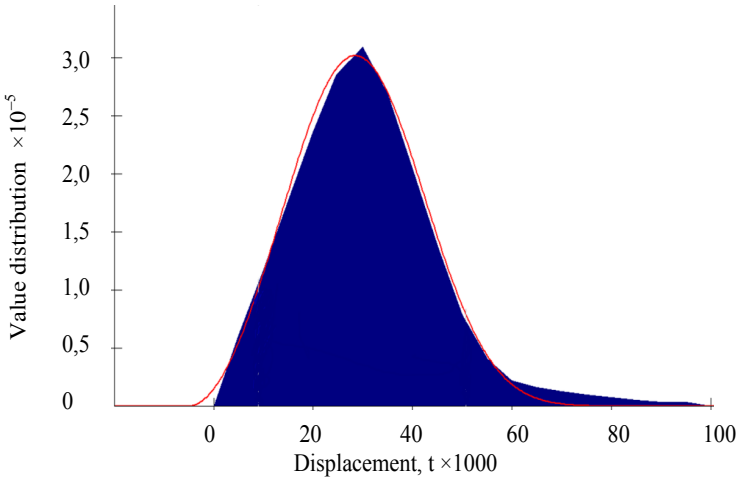

Fig. 6. Displacement distribution for vessels with hazardous cargoes arriving at the port, used in solving the optimization problem

This solution is presented by the following data:

CHARACTERISTICS OF THE OPTIMAL ESCORT TUG

Escort tug length (ET) *L*, m	31,63
Beam *B*, m	1,07
Draft *T*, m	4,01
Moulded depth *H*, m	5,85
Block coefficient	0,505
Midship section coefficient	0,853
Waterplane area coefficient	0,915
Displaced volume, m^3	644,54
Main engine type	3516
Maximum engine power, kW	1201
Maximum speed, kn	11,94
Escort speed, kn	10,00

OPERATIONAL-ECONOMIC FIGURES

Average time of escort voyages requested by port, days	0,18
Average duration of completed voyages, days	0,20
Required average value of the steering force for a selected stream of vessels arriving at the seaport, tons	56,9
Maximum steering force of the tug, tons	69,9
Corresponding braking pull, tons	–69,9
Towline angle corresponding to maximum steering force	45,0

GENERAL OPERATIONAL-ECONOMIC FIGURES

ET daily expenses at cost, $ / day	3384,9
Minimal time charter equivalent for ET charter, $ / day	5412,6
ET design and building cost, million $	5,77
ET life span cost, million $	45,67
Efficiency factor of ET life span, million $	46,35

Discussion. The performed study allows to obtain values of forces acting on the escort tug hull during escorting at conceptual design stage, to determine the optimal characteristics of escort tugs with distribution of the escorted vessels displacements taken into account. Calculation results were compared with the data of full-scale tests and showed a match at the estimated speeds of 8 and 10 knots.

CONCLUSIONS. As a result of development of the described method for determination of the escort tugs main dimensions and characteristics, the following results were obtained:

– for the first time, based on the data of escort tugs towing tests in the NUOS towing tank, a method was developed for determination of the hydrodynamic forces acting on the tug hull, that establish the dependencies of these forces on the orientation of the tug relative to the inflow, flow velocity and characteristics of the hull shape, and that is required for compiling and solving the equations of tug motion based on its operational purpose;

– method for solving the transcendental equations of tug motion was defined. It is similar to the method for solving the optimization problem of determination of tug main dimensions;

– operational purpose of the escort tug was improved by orientation of its main functional operation towards servicing the group of vessels of various types and displacements arriving at the seaport, that allows the escort tugs of certain capacities to serve vessels of certain displacement range more efficiently;

– for the first time the requirements of Classification Societies to safety of escort operations, stipulated due to the need to compensate the lack of handling capacity of the escorted vessels at relatively low speed of escort operations with the high level steering force of the escort tug, were included in the definition of the optimization problem;

– based on the inclusion in the optimization problem of the following points: determination of main dimensions and characteristics of the escort tug, refined definition of operational purpose of the tug, proposed methods for determination of the hydrodynamic forces acting on the tug hull and solutions to transcendental equations of tug motion, as well as new requirements of Classification Societies to safety of escort operations, method for conceptual design of escort tugs received further development.

Список літератури

[1] Azimuth Stern Drive Tug [Electronic resourse] / Damen Shipyards. — Available at : https://products.damen.com.

[2] **Слижевский, Н. Б.** Расчет эскортных характеристик буксира [Текст] / Н. Б. Слижевский, А. С. Марков // Збірник наукових праць УДМТУ. — 2002. — № 7 (385). — С. 3–12.

[3] **Поздеев, В. А.** Метод определения гидродинамических сил, действующих на буксир в режимах эскортных операций [Текст] / В. А. Некрасов, А. П. Ястреба // Збірник наукових праць НУК. — 2010. — № 6. — С. 47–55.

[4] Разработка программного обеспечения для определения максимальной удерживающей силы и угла крена эскортных буксиров в соответствии с требованиями Правил РС [Текст] / А. И. Немзер, А. В. Юрканский, М. А. Кутейников, М.Е. Захаров // Научно-технический сборник Российского морского регистра судоходства. — 2016. — № 42–43. — С. 70 –74.

[5] **Войткунский, Я. И.** Справочник по теории корабля [Текст] : т. 3. Управляемость водоизмещающих судов / Я. И. Войткунский. — Л. : Судостроение, 1985. — 544 с.

[6] Оборудование для экспериментального определения характеристик эскортных буксиров и методика пересчета результатов модельных испытаний на натуру [Текст] / В. А. Некрасов, Д. А. Дробот, С. А. Череватенко, А. П. Ястреба // Інновації в суднобудуванні та океанотехніці (5.10–7.10.2011) : матеріали II Міжнарод. наук.-техн. конф., присвяченої 20-річчю незалежності України / Національний університет кораблебудування імені адмірала Макарова. — М. : НУК, 2011. — С. 88–90.

[7] **Некрасов, В. А.** Определение характеристик эскортных буксиров на основе данных модельных испытаний в опытовом басейне НУК [Текст] / В. А. Некрасов, А. П. Ястреба // Інновації в суднобудуванні та океанотехніці (4.10–6.10.2012) : матеріали III Міжнарод. наук.-техн. конф., присвяченої 75-річчю створення Миколаївської області / Національний університет кораблебудування імені адмірала Макарова. — М. : НУК, 2012. — С. 139–141.

[8] Craneship [Electronic resourse]. — Available at :. www.craneship@.ua.

[9] **Иванов, А.** Робот по имени «Panda» [Текст] / А. Иванов // Судостроение и судоремонт. — 2011. — № 6 (50). — С. 22–29.

[10] **Некрасов, В. А.** Формулировка оптимизационной задачи выбора главных размерений эскортного буксира [Текст] / В. А. Некрасов, А. П. Ястреба // Інновації в суднобудуванні та океанотехніці (20.05–22.05.2015) : матеріали Всеукраїн. наук.-техн. конф. з міжнародною участю «Сучасні технології проектування, побудови, експлуатації і ремонту суден, морських технічних засобів і інженерних споруд» / Національний університет кораблебудування імені адмірала Макарова. — М. : НУК, 2015. — С. 46–47.

[11] IMO. Resolution A. 751(18) [Text], 1993.

[12] Rules for the Classification of Steel Ships [Text] / Bureau Veritas. — Chapter 13, Sec.1, 2, 3. — P. 55–70.

[13] MaxSurf 20 enterprise V8i. Bentley engineering 2013 [Text].

[14] **Гофман, А. Д.** Движительно-рулевой комплекс и маневрирование судна [Текст] : справочник / А. Д. Гофман. — Л. : Судостроение, 1988. — 360 с.

[15] **Химмельблау, Д. Р.** Прикладное нелинейное программирование [Текст] / Д. Р. Химмельблау. — М. : Мир, 1975. — 576 с.

[16] Технический отчет о проведении эскортных испытаний буксира «Пантера», проект TUG60L. TUG60L.360285.005 [Текст]. — Kirgan Holding S.A., 2010. — 9 с.

[17] **Некрасов, В. А.** Исследовательское проектирование эскортных буксиров [Текст] / В. А. Некрасов, А. В. Бондаренко, А. П. Ястреба // Інновації в суднобудуванні та океанотехніці (11.10–13.10.2017) : матеріали VIII Міжнарод. наук.-техн. конф. / Національний університет кораблебудування імені адмірала Макарова. — М. : НУК, 2015. — С. 46–47.

Статтю рекомендує до друку
канд. техн. наук, доц. *О. В. Бондаренко*