Досліджується вплив параметра узгодження «двигун внутрішнього згоряння – турбокомпресор» на витрату палива за строк служби судна за допомогою імітаційної математичної моделі. Встановлено, що для танкера з двигуном 6S50ME-C7 і кайтом 640 м^2 оптимальний параметр відповідає точці узгодження на гвинтовій характеристиці двигуна з координатою по навантаженню 60,5 % від номінального. Економія палива від оптимізації на стадії проектування судна становитиме за строк експлуатації на рейсовій лінії в Північній Атлантиці близько 3 %

Ключові слова: імітаційна модель, малообертовий двигун, турбокомпресор, точка узгодження, кайт, витрата палива

Исследуется влияние параметра согласования «двигатель внутреннего сгорания – турбокомпрессор» на расход топлива за срок службы судна с помощью имитационной математической модели. Установлено, что для танкера с двигателем 6S50ME-C7 и кайтом площадью 640 м^2 оптимальный параметр соответствует точке согласования на винтовой характеристике двигателя с координатой по нагрузке 60,5 % от номинальной. Экономия топлива от оптимизации на стадии проектирования судна составит за срок эксплуатации на рейсовой линии в Северной Атлантике около 3 %

Ключевые слова: имитационная модель, малооборотный двигатель, турбокомпрессор, точка согласования, кайт, расход топлива

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TOOLS FOR FORECASTING AND OPTIMIZING THE TUNING PARAMETER OF THE LOW-SPEED ENGINE FOR DESIGNING A SHIP WITH THE KITE

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1. Introduction

The bulk of the operating costs of a sea transport ship is the cost of fuel spent on its propulsion. The major fuel is consumed by the main engine (ME), which is the most important element of the ship propulsion unit (PU). As the ME, low-speed diesel engines (LSE), having the lowest specific fuel consumption and consuming mostly cheap heavy fuel are most often used. Nevertheless, reduction of fuel consumption remains an urgent problem of ship power engineering.

One of the ways to increase the energy efficiency and environmental friendliness of the ship PS is to minimize the total voyage fuel consumption for the entire ship life and, as a consequence, reduce harmful emissions into the atmosphere.

Modern LSE have significantly approached the limit of thermodynamic perfection, as indicated by the actual stabilization of specific fuel consumption over the past 25 years. However, further development of LSE [1] follows the path of perfection as an element of the ship propulsion system (PS), which, in addition to the PU, may include a kite [2]. If the winds are favorable, the thrust of modern kites can significantly reduce the load of the ME of medium-range vessels with moderate speeds. This leads to expansion of the load range of the ME at full speed of the ship and shifts the dominant load to the region of lower values. The range and the dominant load predetermine the optimum value of the "internal combustion engine – turbocharger" (ICE – TC) matching parameter. This value of the ICE – TC parameter, determined at the ship design stage, will ensure minimum total fuel consumption for the entire life. According to this value, the LSE is set at the engine manufacturing stage, i. e. the TC with the appropriate dimensions of its flowpaths is installed, the compression ratio and gas distribution are regulated [1, 3]. However, there are no recommendations on this issue with regard to transport vessels with a kite. Therefore, obtaining information in this direction is relevant.

2. Literature review and problem statement

For the manufacture of LSE, the ship ME delivery note must specify data for tuning, i.e., the ICE – TC parameter. In general, this is the position of the matching point in the engine layout diagram in the "power – rotational speed" coordinates [1].

A rational LSE tuning corresponds to a certain TC, ensuring a minimum fuel consumption of the ME for the entire future operation of the ship. This method of LSE tuning, when the PU designer sets the position of the matching point in the diagram, was applied to the engines that meet the IMO Tier I environmental requirements [4]. The MAN Diesel & Turbo (MDT) company considers it reasonable to have the matching point on the heavy running (movement of the ship with the fouled hull and in stormy weather) propeller curve of the engine. The point corresponds to its load, lying in the range of 85…100 % of the specification power. In the general case, according to the MDT recommendations, the matching point may be located anywhere in the engine layout diagram. This causes significant uncertainty when making appropriate design decisions. According to [1], each position of the matching point has its own, strictly defined dependence of specific fuel consumption of the LSE on its load. It is a continuous function with an extremum – minimum specific fuel consumption at a certain load. With the decrease of the matching point in the diagram, the extremum shifts to the region of lower load values, and the consumption value in the extremum, for example, for the 6S50ME-C7 engine, – from 160 to 152 g/(kWh). If the high load of the LSE is dominant during the ship operation, then the tuning point should be taken at the top of the engine layout diagram. With the decrease of the dominant load, the matching point is shifted to the bottom of the diagram, which will ensure a lower total fuel consumption for the entire ship's life.

A "discrete" version of LSE tuning, meeting the IMO Tier II or Tier III environmental requirements [4], is one of the possible load ranges. At a high load – 85…100 %, part load – 50…85 %, low load – 25…70 % and one of the LSE tuning programs offered by the MDT company [1]. High load corresponds to a normal, default-set engine, which corresponds to engines with the Tier I environmental impact level [4].

The ME load at full speed varies due to fluctuating ship resistance. Resistance depends on external conditions on the voyage line, which are characterized by variable hydrometeorological parameters: wave height, wind speed and their directions [5]. Also, resistance depends on the technical condition of the underwater hull – roughness, changing with the ship age as a result of corrosion and fouling [6]. Therefore, minimization of fuel consumption, taking into account these changing in operation factors when making design decisions on the PU (based on the relevant calculations) becomes rather reasonable. However, such an approach in providing the ship with maximum energy efficiency has not been revealed in the literature.

In the traditional version of the PU, the fluctuation of load on the ME at full speed is rather small. The value of the dominant load on the ME usually lies in the power range of 80…90 % of the specification power. This range is significantly wider if a controlled kite is used on the ship. The SkySails company has created kites with the area from 80 to 640 m^2 [2, 7], which are intended for use on sea transport ships. The ship kite is an additional propeller with a variable thrust [8], which reduces fuel consumption of the ME. The kite is switched on periodically at favorable wind speeds and directions. The maximum thrust is provided by the kite voyage trajectory in the "eight" form [9]. The useful thrust [10] of a kite with the area of 640 m^2 can reach 320 kN, which is 20…30 % of resistance of the medium-range vessel with a moderate speed. The use of a kite leads to a change in the ME operating mode. And this affects the rational value of the matching parameter.

The MDT company gives general recommendations on the selection of this parameter value for typical sea transport ships. For the traditional version of the PU, when the load range of the ME at full speed is rather small, these recommendations are acceptable in the PU design, and the value of the ICE – TC parameter is determined practically at will. If, when using the kite on the ship, the optimum value of the ICE – TC parameter is set rather than calculated, this can lead to an increase in fuel consumption from the possible minimum [11]. In this case, neither practical recommendations, nor theoretical solutions have been found in the literature. Thus, the procedure for calculating the rational value of this parameter for a particular designed ship is not formalized and refers to the unresolved problems of the theory and practice of ship power engineering.

This prompts the formulation and solution of the problem of calculating the value of the ICE – TC parameter, at which the LSE is adapted best for the forthcoming operating conditions. At the same time, the ship propulsion is ensured by both the constantly operating ME, and periodically switched kite.

3. The aim and objectives of the study

The aim of the study is to develop tools for forecasting and minimizing fuel consumption for the lifetime of a sea transport ship with a kite. Such tool is a simulation mathematical model [12, 13] for determining the total fuel consumption of the ME at the PU design stage for the entire future operation. The practical component of the aim of the study is the determination, in relation to a particular ship with a kite and the accepted voyage line, of the value of the ICE – TC parameter at which the total fuel consumption is minimum.

To achieve this aim, it was necessary:

– to develop a simulation (stochastic) mathematical model (SMM) that includes design data on the ship in a deterministic form, performance characteristics, including hydrometeorological data on the voyage line in a probabilistic form, and a generator with a sufficient number of generated pseudo-random numbers in a cycle;

– to carry out computer experiments based on the specified SMM to obtain the data promoting the rational tuning of the LSE;

– to determine the optimum value of the ICE – TC parameter for the specified ship.

4. Materials and methods of the study

Achievement of the practical component of the aim of the study is associated with decision-making at the ship design stage, so this aim cannot be achieved experimentally. The basis of the study is the construction of a mathematical model for determining the criterion of energy efficiency and the implementation of the statistical modeling method. By the quantitative value of the criterion, design alternatives are compared and a certain decision is made – the rational value of the ICE – TC parameter for a particular ship.

Since the ICE – TC parameter predetermines fuel consumption, it is extremely important that this consumption is calculated adequately to the aim. The calculation is possible if the ship cruising is represented as the sum of the steady-state full speed regimes on sections of the voyage line with the conditionally constant weather. Each section has its own, unchanged in a single calculation, intensity of waves, strength of wind, their directions and, consequently, constant speed of the ship and load on the ME. Fuel consumption for the ship movement on the section will be a product of the ME power, specific fuel consumption and duration of transition of this section.

For a sea transport ship, the voyage line usually passes through several climatic regions [5, 6], each having its own wave intensity, wind strength and their directions. Fig. 1 schematically shows the voyage line with the length L between the departure and arrival ports, divided into transitions with the lengths $L_{\text{CR}1}$, $L_{\text{CR}2}$,..., $L_{\text{CR}f}$,..., $L_{\text{CR}F}$ through climatic regions and sections with the length $l_1, l_2,..., l_i$; the length of the last sections in each climatic region is $l_{\text{CR}1}$, $l_{\text{CR}2}$,..., $l_{\text{CR}f}$,..., $l_{\text{CR}F}$.. This structure of the voyage line allows taking into account the hydrometeorological features of each region in the calculation of fuel consumption, especially in the presence of a kite.

The design decision regarding the ICE – TC parameter is manifested throughout the ship operation, covering about 25-year period. During this period, the roughness of the underwater hull and, consequently, ship resistance change. Due to periodic cleaning and painting of the hull during docking, roughness is reduced to a certain level, not reaching, however, the initial state. In general, additional ship resistance caused by roughness is a piecewise discontinuous function of the ship age [6]. Discontinuity is caused by the ship out of exploitation for docking and factory repairs. The combination of inter-docking periods, docking and factory repairs form unique maintenance and repair cycles (Fig. 2). By simulation of such cycles, it becomes possible to determine the useful operating time and, taking the berthing time, calculate the total sea days throughout the ship operation. In addition, no less important, the ship age, on which additional corrosion and fouling resistance depends can be calculated for each section of the voyage line.

Alternative values of the ICE – TC parameter by their nature cannot affect the characteristics of the voyage line (Fig. 1) and maintenance and repair cycles (Fig. 2), and, therefore, the target efficiency of the ship as a transport unit. It can also be assumed that they will not have any noticeable effect on the ship cost. This makes it possible to take the total fuel consumption of the ME for the entire ship operation as a criterion of the comparative efficiency of the values of the ICE – TC matching parameter, defined as

$$B_L = N_s \sum_{i=1}^{I} \left(\bar{N} b t\right)_i, \tag{1}$$

where N_s is the specification power of the ME; $\bar{N}_i$ is the load on the ME on the i-th section of the voyage line; b_i is the specific fuel consumption corresponding to the load $\bar{N}_i$; t_i is the sea days on the i-th section of the voyage line; i=1, 2,..., I, here I is the number of sections with conditionally constant weather for the entire ship's life.

Fig. 3 presents the enlarged form of the structure of the process of determining the rational value of the ICE – TC parameter, at which the weighted average fuel consumption for the entire ship's life will be minimum, i.e., the expected value of fuel consumption $M\left(B_L\right) = B_L^{\min}$.

Each cruise, each section of the voyage line, technical condition of the ship throughout the operation are characterized by both constant and variable (usually probabilistic) parameters. Therefore, different values of the same initial probabilistic quantities simulated in repeated calculations are used in the mathematical model for calculating the B_L (Fig. 3). This allows simulating possible operational situations with a given degree of completeness. Consequently, the calculation of B_L as a random objective function determines the use of the simulation (stochastic) mathematical model.

Determination of the optimum coordinates $\bar{N}_m^{\text{opt}}$, $\bar{n}_m^{\text{opt}}$ and the corresponding rational TC is achieved by the statement and solution of the optimization problem by comparing the design alternatives according to the criterion of fuel consumption. As follows from Fig. 3, the solution of the problem lies in the fact that a certain number (M) of alternative values of the ICE – TC parameter is given. Each value corresponds to a specific turbocharger: TC-1, TC-2, ..., TC-M. With these values, using a pseudo-random number generator – uniformly distributed (PRNG-ud), N^* dimension arrays of possible fuel consumption values $\{B_{Lm}\}_{N^*}$, m=1, 2,..., M are calculated. The expected values of fuel consumption $M(B_{Lm})$ are calculated, and the minimum consumption value corresponds to the optimum value of the ICE – TC parameter, which determines the rational TC.

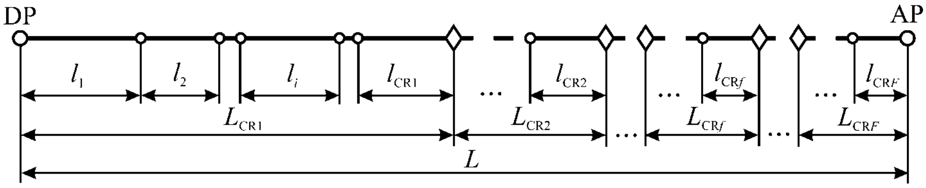

Fig. 1. Voyage line with transitions in climatic regions and sections with the conditionally constant weather with the lengths L, $L_{\text{CR}f}$ and l_i, respectively: DP — departure port; AP — arrival port

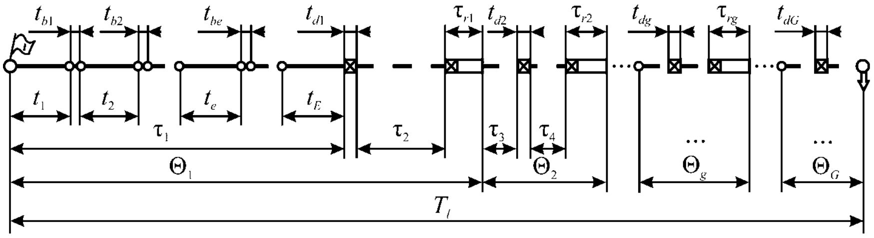

Fig. 2. Ship maintenance and repair cycles of duration Θ_1, Θ_2,..., Θ_g,..., Θ_G for the life T_l: sea days t_e and berthing time t_{be} in the e-th cruise e=1, 2,..., E; duration of docking t_{dg} and factory repair τ_{rg} in the g-th cycle g=1, 2,..., G; inter- docking periods τ_1, τ_2, τ_3, τ_4,...

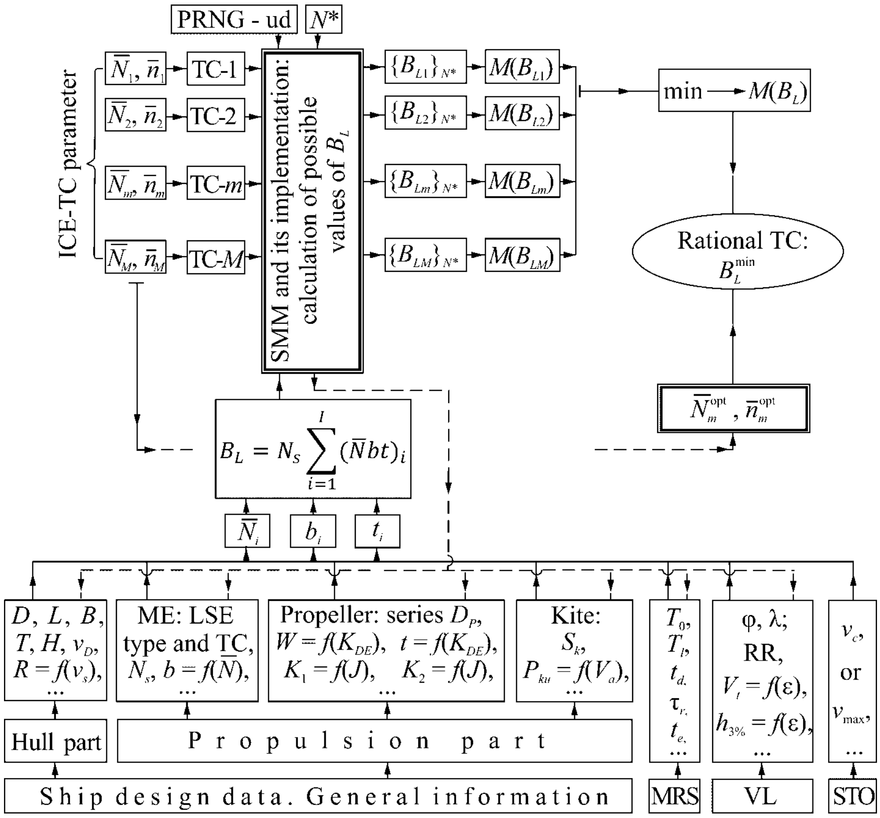

Fig. 3. Structure and substance of the simulation mathematical model for obtaining an array of values $\{B_L\}$, expected value $M(B_L)$ and determining the optimum coordinates $\bar{N}_m^{\text{opt}}$, $\bar{n}_m^{\text{opt}}$ of the ICE – TC parameter with $M(B_L)=B_L^{\min}$ (dashed line – transfer of a set of random numbers from the "PRNG-ud" block to calculate the indeterminate values in each subsequent life cycle of the ship)

The mathematical model is based on the equation for determining the fuel consumption of the ME at the i-th section of the voyage line (with conditionally constant weather)

$$B_i = N_s \bar{N}_i b_i t_i, \tag{2}$$

in which the specification power of the LSE N_s is a deterministic quantity, and the engine load $\bar{N}_i$, its specific fuel consumption b_i and the transition time t_i on the i-th section are random functions. The calculation of these random functions requires appropriate techniques and extensive information on the design, manufacture and operation.

The basic information – initial data, functional dependencies and calculated values, as well as the notations in Fig. 3, are as follows:

D – displacement; L, B, T, H – length, width, draft and height of the board; v_D –design speed; $R=f(v_s)$ – ship resistance, depending on its speed – *by the hull part*;

LSE – low-speed engine; TC – turbocharger; N_s – specification power; $b=f(\bar{N})$ – specific fuel consumption depending on the engine load – *by the main engine (ME)*;

D_P – diameter; $W=f(K_{DE})$ and $t=f(K_{DE})$ – estimated wake and thrust-deduction fractions, respectively, depending on the propeller traction-load coefficient [14]; $K_1=f(J)$ and $K_2=f(J)$ – propeller thrust and torque coefficients, respectively, as a function of advance ratio – *by the propeller (P)*;

S_k – area; $P_{ku}=f(V_a)$ – useful thrust, depending on the imaginary (apparent) wind speed – *by the kite*;

T_0 – beginning (date) of ship commissioning; T_l – ship's life; t_d, τ_r and t_e – duration of docking, repair and e-th cruise, respectively – *by the maintenance and repair schedule (MRS)*;

φ, λ – geographic coordinates (longitude and latitude) of departure and arrival ports; RR – recommended route; $V_t=f(\varepsilon)$ and $h_{3\%}=f(\varepsilon)$ – inverse integral distribution functions of true wind velocity and wave height of 3 % probability – *by the voyage line (VL)*;

v_c – commercial speed; $v_{\max}$ – maximum possible speed, with the observance of navigation safety – *by the ship traffic organization (STO)*.

Since the hydrometeorological parameters, kite thrust, hull roughness, route length in the section with conditionally constant weather are variable during the ship operation, $\bar{N}_i$, b_i and t_i in each calculation take different values. Calculation of B_L is possible if the initial ambiguous quantities are presented in a probabilistic-determined form, which allows applying the statistical modeling method [12, 13], using a random number generator.

In this study, the SMM with a pseudo-random number generator with the 0...1 interval (PRNG-ud) set for uniformly distributed numbers was developed and used. To ensure the necessary adequacy of the SMM in terms of comparability of alternative values of the ICE – TC parameter, the PRNG-ud with at least 10^{12} generated numbers in the cycle is used. It consists of three subprograms: OpenCryptRandom, CryptRandom, and CryptRandomData [15]. This generator predetermines the representation of the distribution laws of the values of indeterminate quantities normalized on the 0...1 interval in the form of inverse integral functions [13]. In the simulation, the number of repeating calculations,

i. e., a sufficient number of statistical tests N^* (Fig. 3) on a computer, is related to the given initial data [13].

5. Determination of the optimum value of the ICE – TC parameter

The calculation of the ICE – TC parameter for completing and tuning the LSE makes sense to implement in relation to a specific transport ship at the design stage. At the same time, it is important to have information about the forthcoming voyage lines, on which it is expected to operate. As an object of the study and to illustrate the results of simulation, the "Dmitry Medvedev" medium-range tanker [6] with the LSE of the MDT company and a 640 m^2 SkySails kite was taken. By parameters, this tanker is similar to the "Aghia Marina" bulk carrier with a length of 170 m [2], which uses the same kite.

Tanker specifications:

– displacement of 35,970 m, deadweight of 26,470 tons;

– principal dimensions – overall length is 178.8 m, the length between perpendiculars is 165.0 m, the depth is 15.0 m, the load waterline draft is 10.4 m;

– ME – modern LSE 6S50ME-C7 [1] with a specification power of 9,006 kW and a rotational speed of 127 min^{-1};

– turbocharger of the ME – TCA axial turbocharger of the MDT company, the outer diameter of the turbine wheel of which, depending on the alternative ICE – TC matching parameter, lies in the range of 55...66 cm;

– achievable deep and calm water speed of the ship with a freshly colored uncorroded hull during the ME operation of 15.1 knots;

– propellers – a four-bladed fixed-pitch propeller with a diameter of 5.5 m and SKS 640 kite, activated if the winds are favorable, at a speed within 4...20 m/s.

Full-scale tests of ship kites were conducted in various water areas in different years with SKS kites ranging from 80 to 640 m^2 on motor ships of different lengths:

– "MS Beaufort" pilot ship – 2006, 80 m^2 and 160 m^2, 55 m;

– "Michael A" dry cargo ship – 2007 – 2008, 160 m^2, 87.6 m;

– "Theseus" dry cargo ship – 2007– 2008, 160 m^2, 89.7 m;

– "Beluga" dry cargo ship – 2008 – 2009, 160 and 320 m^2, 132 m;

– "Maartje Theadora" trawler – 2010, 160 m^2, 140.8 m;

– "Aghia Marina" bulk carrier – 2012, 320 m^2, 170 m [2].

Extensive tests of kites with the area of 160 m^2 (2007) and 320 m^2 (2009) were carried out on the "Beluga" dry cargo ship in the Northern Atlantic. The tests made it possible to obtain, in particular, the dependence of the useful specific thrust of the kite on the speed and direction of the imaginary wind relative to the ship's course [2, 11].

The developed SMM was implemented with reference to a round voyage also in the Northern Atlantic along the recommended route of 9,825 miles between the ports of Brest (France), Santa Maria (Cape Verde), La Guaira (Venezuela), Boston (USA) and Brest.

For completeness of the study, different tanker loads were considered: from the port of Brest, the ship loaded with gasoline and kerosene goes to the port of Santa Maria; then to the port of La Guaira – in ballast; to the port of Boston loaded with heavy oil; comes back to the port of Brest with diesel fuel.

The voyage line crosses nine climatic regions. For each region, there are frequency tables of wave heights of 3 % probability and wind speed and direction by seasons [5]. For these regions, the inverse integral distribution functions of the values of these random variables normalized on the 0...1 interval were obtained.

Table 1 shows the main performance characteristics of the tankers equipped with a 640 m^2 kite and 6S50ME-C7 engines, differing in alternative values of the ICE – TC parameter. The deterministic characteristics are the ship's life, operating time and sea days, length of the voyage line according to the recommended route, the rest are indeterminate, for which their expected values are given.

Table 1

Estimated performance characteristics for the "Dmitry Medvedev" type tankers

Characteristics	Units of measure	Value
Ship's life T_l	Years	25
Duration:		
– operation:		
– absolute T_o	days (years)	8,686 (23.8)
– in relation to T_l	%	95.2
– cruising:		
– absolute T_c	days (years)	7,754 (21.24)
– in relation to T_o	%	89.2
– kite operation:		
– absolute	days (years)	5,001 (13.7)
– in relation to T_c	%	64.5
Voyage line length:		
along the recommended route	Miles	9,825
actual	Miles	10,189
Number of voyages	–	256
Speed	knots	13.46
Ship resistance	kN	620
Propeller thrust	kN	484
Kite useful thrust	kN	136

As alternative values of the ICE – TC parameter, the coordinates of seven points in the L_1–L_2–L_3–L_4 diagram [1], located on the heavy running propeller curve of the LSE are taken. Table 2 shows these coordinates and the corresponding fuel consumption for the entire ship's life, obtained by implementing the SMM with N^*=1,000, although the stabilization of the expected value $M(B_L)$ is observed even with $N^*\cong 400$. Fuel consumption in Table 2 corresponds to the data of Table 1, which relates to the organization of ship traffic in liner shipping with an average commercial speed of v_s=idem (in this case, v_s=13.46 kn).

According to the data of Table 2, Fig. 4 shows the dependence of fuel consumption on the $\bar{N}$ coordinate – relative power in the L_1–L_2–L_3–L_4 diagram, which determines the ICE – TC parameter lying on the heavy running propeller curve of the LSE. The minimum of the function

$$M(B_L) = f(\bar{N})$$

corresponds to the optimum coordinate of the ICE – TC matching parameter $\bar{N}_o = 60.5$ %.

Table 2

Fuel consumption of the ME for the entire life of "Dmitry Medvedev" type tankers with 6S50ME-C7 engines and SKS 640 kite, differing in the ICE – TC parameter

Alternative values: absolute and relative power and, in parentheses, rotational speed in the L$_1$–L$_2$–L$_3$–L$_4$ diagram		Fuel consumption					
		absolute, thousand tons			specific, kg/mile		
kW (rpm)	%	min	max	$M(B_L)$	min	max	$M(B_{RR})$
9006.0 (121.7)	95.0 (95.9)	144.3	178.8	154.8	57.4	71.1	61.5
8290.7 (118.5)	87.5 (93.3)	142.9	177.1	153.3	56.8	70.4	60.9
7575.3 (115.0)	79.9 (90.5)	141.6	175.4	151.9	56.3	69.7	60.4
6860.0 (111.3)	72.4 (87.6)	140.6	174.3	150.9	55.9	69.3	60.0
6144.7 (107.3)	64.8 (84.5)	139.9	173.4	150.1	55.6	68.9	59.7
5429.3 (103.0)	57.3 (81.1)	140.0	173.5	150.2	55.7	69.0	59.7
4714.0 (98.3)	49.7 (77.4)	142.2	176.3	152.6	56.5	70.1	60.7

Note:

1) $M(B_L)$, $M(B_{RR})$ – expected value of fuel consumption;

2) $M(B_{RR})$ – in relation to the length of the recommended route

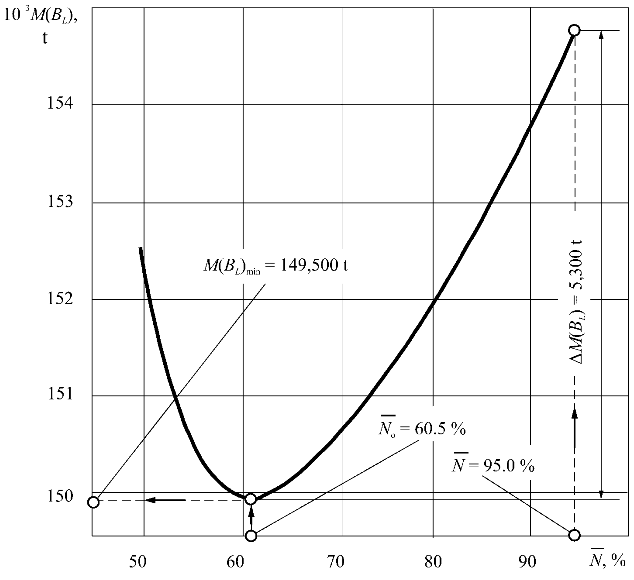

Fig. 4. Fuel consumption of the ME for the entire life of "Dmitry Medvedev" type tankers, depending on the coordinate of the ICE – TC matching point in the L_1–L_2–L_3–L_4 diagram

Table 3 shows the values calculated by means of SMM, characterizing the efficiency of using different kite sizes on "Dmitry Medvedev" type tankers, and the indicators of the ICE – TC parameter optimization at a heavy fuel price of 322 USD/t. Here, specific fuel consumption is calculated in relation to the actual route passed.

In [16, 17], a significant dependence of fuel economy due to a kite on the hydrometeorological parameters of the voyage line is indicated. Savings in direct and return voyages are not the same, ranging from 4 to 36 % at the operating speed of transport ships of 13 knots. In Fig. 5, characteristic voyage lines of the world merchant fleet [16, 17] and round voyage between the designated ports for the "Dmitry Medvedev" type tanker are combined. In the same place for the Northern Atlantic, the prevailing westerlies and northeast trade winds are indicated. On two transit lines – transatlantic (No. 1) and transpacific (No. 2), fuel economy is significantly, on average 23 and 22 %, higher than on the other 13 lines.

Table 3

Efficiency of the kite use on "Dmitry Medvedev" type tankers and the ICE – TC parameter optimization at a heavy fuel price of 322 USD/t

Characteristics		Kite area, m^2			
		0 (without a kite)	160	320	640
Without optimization of the ICE – TC parameter					
Expected value of ME fuel consumption	for the ship's life, thousand tons	184.10	168.92	160.35	145.53
	specific, kg/mile	73.48	67.42	64.00	58.09
Fuel economy	for the ship's life, thousand tons	–	15.18	23.75	38.57
	%	–	8.25	12.90	20.95
Reduction of fuel consumption	for the ship's life, USD thousand	–	4,889	7,648	12,420
	USD thousand/year	–	196	306	498
With optimization of the ICE – TC parameter					
Expected value of fuel consumption on the ME	for the ship's life, thousand tons	182.42	165.51	156.08	139.23
	specific, kg/mile	72.84	66.06	62.30	55.57
Fuel economy	for the ship's life, thousand tons	1.68	18.59	28.02	44.87
	%	0.91	10.10	15.22	24.37
Reduction of fuel consumption	for the ship's life, USD thousand	541	5,986	9,022	14,448
	USD thousand/year	22	239	361	578
Effect of optimization of the ICE – TC parameter					
Fuel economy	for the ship's life, thousand tons	1.68	3.41	4.27	6.3
	%	0.91	1.85	2.32	3.42
Reduction of fuel consumption	for the ship's life, USD thousand	541	1,098	1,375	2,029
	USD thousand/year	22	44	55	81

The calculated expected value of fuel economy in a round voyage of a tanker with a 640 m^2 kite is 21 %. Almost the same fuel economy in these transoceanic lines can be explained by the same type of prevailing westerlies and northeast trade winds.

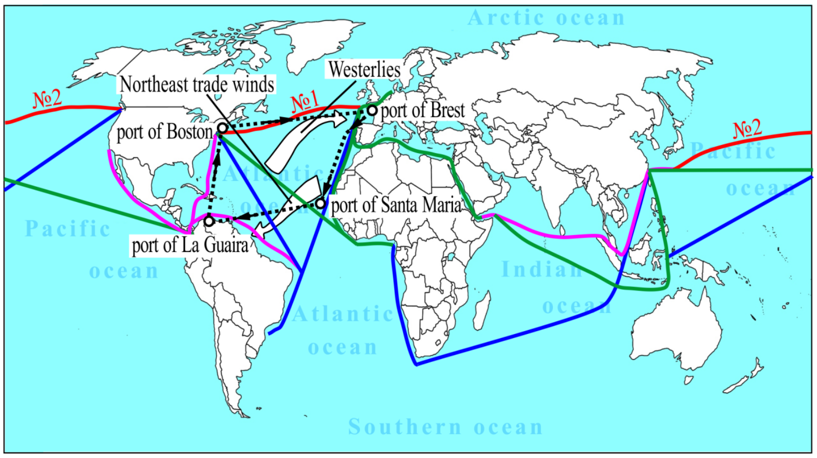

Fig. 5. Characteristic voyage lines of the world transport fleet and round voyage the "Dmitry Medvedev" type tanker

6. Discussion of results of calculation of total fuel consumption of the ME of the medium-range tanker

A round voyage chosen to illustrate the achievable efficiency of the kite use and ICE – TC parameter optimization should be considered as the most preferable. In the water area where the voyage is going on, the strength and direction of the prevailing winds are very favorable for the kite operation, which reduces the load on the main engine. According to Table 1, the expected value of the useful thrust of a kite with the area of 640 m^2 is almost 22 % of ship resistance.

The analysis of Table 2 shows that the range of possible fuel consumption at the same value of the ICE – TC parameter is rather wide (19...24 %). Fluctuation of the expected value of fuel consumption in the region of the considered values of the ICE – TC parameter is ~3.5 %. This excludes any initial averaging of hydrometeorological parameters on the voyage line, the application of average values of the kite thrust and other parameters that vary with the ship's age from the calculations. It becomes obvious that simulation is needed to determine the weighted average value of the objective function – in this case, the expected value of fuel consumption for the ship's life $M(B_L)$.

According to the recommendations of the MDT company, it is advisable to place the ICE – TC matching point on the heavy running propeller curve of the engine in the L_1–L_2–L_3–L_4 diagram. In this case, the dependence of fuel consumption on the ICE – TC parameter is represented by the function $M(B_L)=f(\bar{N})$, shown in Fig. 4. This function has an extremum. The minimum fuel consumption $M(B_L)_{\min}$ determines the optimum value $\bar{N}_o = 60.5$ % of the ICE – TC parameter ($\bar{n}_o = 82.6$ %, respectively).

In the established practice of decision-making when designing a ship propulsion unit, the power at the matching point of the ICE – TC parameter is often equal to the specification one, which in this case is 95 % of the nominal value. Then the value of $\Delta M(B_L)$=5,300 t in Fig. 4 represents the fuel economy due to the optimization of the ICE – TC parameter.

With the increase in the kite area, fuel economy due to its use grows, the range of loads of the main engine in liner shipping is extended and one can expect a greater positive effect of optimization of the ICE – TC parameter. Implementation of the SMM allowed establishing the growth dynamics of this effect: fuel consumption is reduced from 1.85 to 3.42 % when using a kite with the area from 160 to 640 m^2. At the same time, the reduction of fuel consumption is USD 2,029 thousand for the life of the "Dmitry Medvedev" type tanker (Table 3).

Comparison of the results of fuel economy in relation to the specified tanker with the data [16, 17] indicates their practical coincidence in the areas of prevailing winds. The efficiency due to optimization of the ICE – TC parameter will be greater where there are significant savings from the use of the kite. Thus, the optimization of the ICE – TC parameter should primarily be applied to vessels with moderate speeds (up to 14 knots), which are to be operated on transatlantic and transpacific voyage lines. These vessels include bulk carriers and tankers.

The scope of application of this study is limited to transport vessels with liner shipping on ocean voyage lines. These are designed motor ships, which are supposed to be equipped with a low-speed engine and a kite of the largest possible area. The quantitative indicators are more or less applied to the vessels that are close in their basic dimensions and speeds to a medium-range tanker, whose operation is provided on transatlantic voyage lines. These lines have a kite-favorable wind potential, due to the prevailing westerlies and northeast trade winds. At the same time, the ME load range is rather wide and the effect of optimization of the ICE – TC parameter is significant. On other voyage lines, this effect will be lower, but, based on fuel consumption, will always be positive.

With other initial data, fuel consumption reduction can be judged after appropriate calculations, using, for example, the proposed SMM structure. At the same time, it can be noted that with the enlargement of ships and especially with the increase in their speed, the positive effect of optimization of the ICE – TC parameter will fall. However, with the creation of larger kites, this effect will become more and more significant.

7. Conclusions

1. The structure of the simulation (stochastic) mathematical model to determine the array of possible values and the expected value of total fuel consumption of the ME for the life of a transport ship with a kite is proposed. This model, filled with generalized deterministic and stochastic (in the form of inverse integral distribution functions) information, together with a pseudo-random number generator, is a tool for optimizing the ICE – TC matching parameter at the ship design stage. Such a tool allows estimating the effect of the LSE tunings on the total fuel consumption and calculating this consumption with an accuracy that is acceptable for comparing the alternative values of the ICE – TC parameter.

2. The original SMM was developed for a medium-range tanker with a deadweight of 26,470 t and average commercial speed of about 13.5 knots, 6S50ME-C7 main engine and SKS 640 kite for a round voyage between ports in the

Northern Atlantic. The SMM includes the PRNG-ud with at least 10^{12} generated numbers in a cycle. The model uses both deterministic and probabilistic values, represented as inverse integral distribution functions. By replacing specifications of the hull, ME, propeller and kite and introducing the parameters of the required voyage line, the SMM becomes suitable for optimization of the ICE – TC parameter of the corresponding ship, whose operation is provided on this line.

3. The computer experiments with the developed SMM allowed obtaining the following information, which contributes to making a rational design decision for the LSE tuning:

– optimization of the ICE – TC parameter gives fuel economy, which essentially depends on the presence of the kite on board and its dimensions. For example, for a tanker with a deadweight of 26,470 tons and average operating speed of about 13.5 knots on the transatlantic line, mainly in the temperate latitudes of the Northern Atlantic, fuel economy is 0.9...3.4 % (as the kite area increases; the larger value corresponds to its area of 640 m^2);

– for the "Brest – Santa Maria – La Guaira – Boston – Brest" voyage line with prevailing westerlies and northeast trade winds, the optimum coordinate of the ICE – TC parameter by power is 60.5 % of L_1, which corresponds approximately to the boundary between Part load – Low load.

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