UDC 62-843.6

# RATIONAL MODES OF OPERATION FOR A FOUR-ARM TILLER ELECTRO-HYDRAULIC STEERING GEAR WITH RESPECT TO MULTI-ALTERNATIVENESS AND PREFERENCES

***Goncharenko A.V.***

*It is investigated the expediency of application of a four-arm tiller electro-hydraulic steering gear equipped with piston hydro-cylinders instead of the plunger steering engine 4EP220, Stork (the Netherlands), for a general dry cargo vessel, 13,500 t DWT and 18.2 knots speed. Substantiation of the effectiveness of the retrofitted steering gear is fulfilled with the help of suitable mathematical modeling illustrated with corresponding plots. It is shown the role of multi-alternativeness, preferences, entropy, and conflicts in the process of operational control.*

*Keywords: electro-hydraulic steering gear, dry cargo vessel, subjective analysis, subjective entropy, individual preferences, multi-alternative situations, conflicts of preferences, canonical distributions, variational principle.*

**Introduction.** Accordingly to [1], electro-hydraulic steering gears (EHSG) are widely used in the world marine ships' fleet. Due to their substantial advantages (compactness, small masses and dimensions, convenience for being automated, reliability, and effectiveness of operation, higher accuracy in control of the helm/rudder and correspondingly holding the ship at a course, ability to bear significant overloading without operational characteristics getting worse etc.); these engines successfully supplanted got old types of steering gears: steam, electric, and hand controlled [1]. The choice of a proper operational mode for steering engines is made by the active element (human/individual) of the operational control system with respect to multi-alternativeness of operational situations and at conditions of possible conflicts of subjective preferences [2-7].

**Urgency of researches.** The urgency of researches is based upon the necessity to reduce the mentioned above overloading of steering gears. It is important to have a decrease in forces acting in EHSG during their operation. The same to the field of human factor influence upon the process of rational and safety operation.

**Analysis of the latest researches and publications.** All machinery-building firms of the developed countries manufacture steering gears [1]. Since the previous fundamental researches represented in monographs [3, 4] and the newest publications [2, 5-7], the method of subjective analysis has been applied to solving problems of control in active systems.

The developed theoretical apparatus is supposed to be applied to the still unsolved part of the problem. Particularly in this paper, it is the substantiation of the expediency of the four-arm tiller EHSG usage. And in the further publications the conflict of individuals' preferences is to be researched.

**The task setting.** Thus, the purpose of this paper is to research the advantages of a four-arm tiller EHSG application. That is the first (introductory) part of a bigger problem of making the choice of the EHSG rational modes of operation in conditions of multi-alternativeness and possible conflicts.

**The main content (material).** The idea is to improve the drive of a plunger EHSG with a structure of a four-arm tiller in conjunction with application of piston hydraulic cylinders instead of the plunger ones. We foresee to get an advantage in forces acting in the cylinders at greater angles of the ship's helm blade deflection. Also, there is an opportunity of choice of the combined mode of operation which suites the best the researched concept. And the concept itself on conditions of multi-alternativeness and possible conflicts implies involvement of subjective individuals' preferences.

Made simplifications are as following: we neglect most forces of resistance, inertiality of the system, suppose equilibrium/steady state, assume predictable operational information and data of EHSG.

 

For expositional ease the vast majority of the intermediate mathematical expressions are omitted.

**The problem formulation.** For a widely used plunger EHSG the sketch of forces and moments acting in the engine is shown in fig. 1.

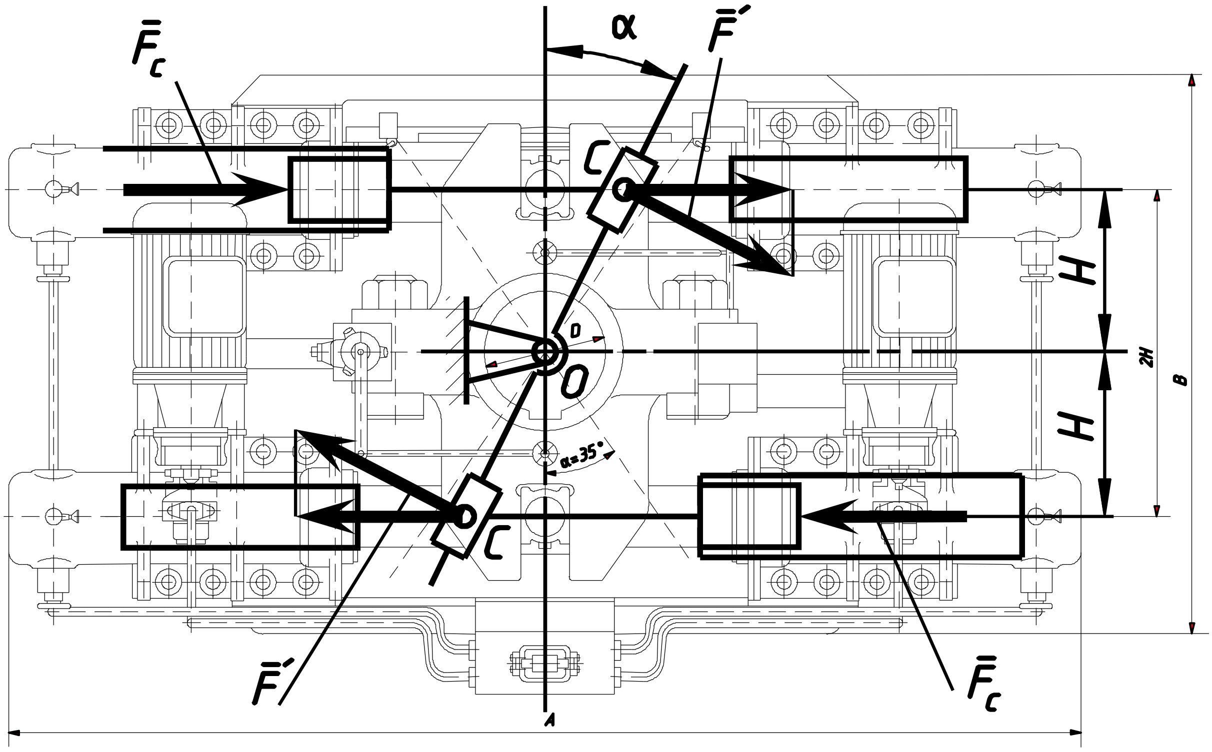


Figure 1 – Scheme of forces and moments acting in a plunger EHSG

On conditions of just statics equilibrium, which is acceptable for a simplified problem setting and represents not a transient process but a steady one, accordingly to the scheme in fig. 1, the force acting in the hydro-cylinder, therefore, for the roughly evaluations is

$$F_c = \frac{M_b \cos^2 \alpha}{2H}, \tag{1}$$

where $F_c$ – force acting in the hydro-cylinder (see fig. 1); $M_b$ – moment acting on the rudder; $\alpha$ – angle of the tiller turning (see fig. 1); $H$ – half-a-distance between axes of the plungers motions, the arm of the force $F_c$ action applied to the plunger in the hydro-cylinder (see fig. 1).

In accordance with the methods presented in [1], the moment acting on the rudder, with taking into consideration the forces of friction in the bearings of the steering engine, is

$$M_b = (1.2\ .\ .\ .\ 1.3)M_a, \tag{2}$$

where $M_a$ – hydrodynamic moment at the helm blade.

The hydrodynamic moment will be determined by the expression [1]

$$M_\alpha = \frac{C_n k_k k_g \rho v_0^2 F (C_d b - b_1)}{2}, \tag{3}$$

where $C_n$ – coefficient of the normal force; $k_k$ – coefficient that evaluates the influence of the ship's hull; $k_g$ – coefficient that evaluates the influence of the ship's propeller; $\rho$ – mass density of the sea water on an average; $v_0$ – speed of flow that attacks the ship's helm blade; $F$ – squared area of the ship's helm blade; $C_d$ – empirical coefficient that evaluates the location of the normal force application point; $b$ – width of the ship's helm blade; $b_1$ – width of the balancing part of the helm blade.

For the four-arm tiller EHSG the scheme of forces and moments acting in the system is depicted in fig. 2.

In such a case, when a four-arm tiller EHSG is installed on board a ship, for the situation when the four-arm tiller EHSG provides the same speed of the helm deflection as the previously considered plunger one, also the four-arm tiller EHSG warranties the development of the identical to the plunger engine moment at the rudder, thus the powers of the both steering gears are the same, there are a few modes of operation for the four-arm tiller EHSG.

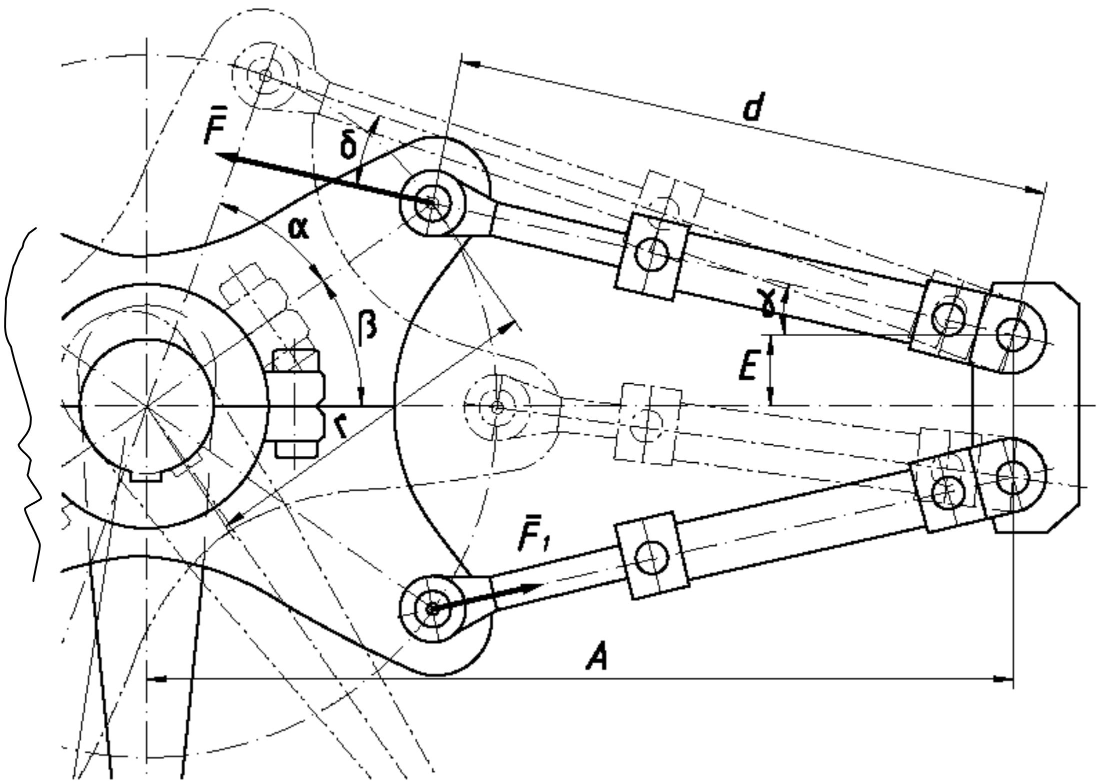


Figure 2 – Scheme of forces and moments acting in a four-arm tiller EHSG

We will now consider the simplest elementary operational modes for the four-arm tiller EHSG equipped with the piston hydro-cylinders (see fig. 2).

For the first mode of operation, it is working the two diagonal hydro-cylinders, pushing their rods out, with the other two cylinders staying idle (see fig. 2). For such a mode of operation the force acting in the running hydro-cylinders will be

$$F' = \frac{M_b}{2r\sin(\alpha+\beta+\gamma+\delta)}, \qquad (4)$$

where $F'$ – force acting in the running hydro-cylinders, that is $\overline{F}$ (see fig. 2), in the case if the first mode of operation is applied; $r$, $\alpha$, $\beta$, $\gamma$, $\delta$ – structure parameters of the four-arm tiller EHSG equipped with the hydro-cylinders; meaning of these parameters denoted in formula (4) and other parameters of the considered EHSG is obviously interpreted from the scheme shown in fig. 2.

The angle of deflection of the working cylinder will make up to the value

$$\delta = -\gamma - arctg\frac{r\sin(\alpha+\beta)-E}{r\cos(\alpha+\beta)-A}, \qquad (5)$$

where $E$ , $A$ – structure parameters of the considered EHSG; again, their meaning is explicitly clear from the scheme shown in fig. 2, for the mentioned above expositional ease we deliberately omit their intermediate mathematical derivations and expressing them through the angles and distances.

For the second mode of operation, we consider the first two diagonal hydro-cylinders working for pushing their rods out and the other two diagonal hydro-cylinders are running with pulling their rods in (retracting them) (see the exactly corresponding situation in fig. 2). For such a mode of operation the force acting in the running hydro-cylinders will be

$$F'' = \frac{M_b}{2r\left[\sin(\alpha+\beta+\gamma+\delta) + 0.75\sin(\beta-\alpha+\gamma-\delta')\right]}, \tag{6}$$

where $\delta'$ – angle of deflection for the hydro-cylinder which retracts its rod. In formula (6) it is implied that on conditions of the same hydraulic pressure the retracting its rod cylinder develops just as much of its force as 0.75 of that one of the pushing out hydraulic cylinder. That is because of the differences in the active areas of their pistons.

The angle of deflection for the hydro-cylinder which pulls in its rod will constitute as much as up to

$$\delta' = \gamma + arctg\frac{r\sin(\beta-\alpha) - E}{r\cos(\beta-\alpha) - A}. \tag{7}$$

Then, for the third of the considered elementary modes of operation, when all four cylinders are working for pushing their piston rods out, we will get the corresponding expressions

$$F''' = \frac{M_b}{2r\left[\sin(\alpha+\beta+\gamma+\delta) + \sin(\alpha-\beta+\delta''-\gamma)\right]}, \tag{8}$$

where $\delta''$ – angle of deflection for the lower hydro-cylinder depicted on the sketch in fig. 2.

This angle is determined by

$$\delta'' = \gamma - arctg\frac{E + r\sin(\alpha-\beta)}{r\cos(\alpha-\beta) - A}. \tag{9}$$

Formulas (7) and (9) are identical.

As we can see now there are a few modes of operation for EHSG, the so called options or alternatives that an individual may choose. Individual's subjective preferences determine the choice. In subjective analysis [2-7] there is a great discussion on the theme of optimality of human's behavior aimed at, and subjective preferences distributed on, the set of alternatives in a problem-resource situation under uncertainty. This optimality is postulated and mathematically this concept is formulated as finding extremums (maxima or minima) of a certain functional that contains a measure of a certain individual's subjective uncertainty regarding to the set of achievable for him/her alternatives. The functional is expressed in a rather general view [3, P. 119, (3.38)]

$$\Phi_\pi = \alpha H_\pi + \beta\varepsilon + \gamma \mathrm{N}, \tag{10}$$

where $\pi$ – function of the individual's subjective preferences; $H_\pi$ –subjective entropy; $\varepsilon = \varepsilon(\pi, U, \ldots)$ – function of subjective effectiveness; N – normalizing condition; $\alpha$, $\beta$, $\gamma$ – structural parameters, they can be considered in different situations as Lagrange coefficients, weight coefficients or endogenous parameters which represent certain psychic properties.

For this problem formulation we might take the functional either in the view of (10) or in the view of its natural extension and generalization for the case of dynamical modelling of control of operational processes developing in time. Such an approach implies the Euler-

Lagrange variational principles. Thus, the postulated functional now is being written in the form of [5, P. 57, (1)]

$$\Phi_\pi = \int_{t_0}^{t_1} \left( -\sum_{i=1}^{N} \pi_i(t) \ln \pi_i(t) + \beta \sum_{i=1}^{N} \pi_i(t) F_i + \gamma \left[ \sum_{i=1}^{N} \pi_i(t) - 1 \right] \right) dt, \qquad (11)$$

where $t$ – time; $-\sum_{i=1}^{N} \pi_i(t) \ln \pi_i(t)$ – entropy of subjective preferences of $\pi_i(t)$; $N$ – number of the achievable alternatives; $F_i$ – subjective efficiency function of the $i^{th}$ alternative; $\sum_{i=1}^{N} \pi_i(t) - 1$ – normalizing condition.

Taking the functional in the view of (10) or (11) we come to canonical distributions of preferences [3, P. 115-135]. For this problem setting we briefly consider the set of two achievable alternatives and in the next and subsequent papers we will be researching the topic in more depth.

If the set of alternatives consists of two optional modes of EHSG operation, let us say, $F'$ and $F''$, then functional (10) will be

$$\Phi_\pi = -\sum_{i=1}^{2} \pi_i \ln \pi_i - \beta \sum_{i=1}^{2} \pi_i F^i + \gamma \left[ \sum_{i=1}^{2} \pi_i - 1 \right]. \qquad (12)$$

Solving (12) for necessary conditions of extremum

$$\frac{\partial \Phi_\pi}{\partial \pi_i} = 0, \qquad (13)$$

we get the desired canonical distributions of preferences

$$\pi_1 = \frac{e^{-\beta F'}}{e^{-\beta F'} + e^{-\beta F''}}, \qquad \pi_2 = \frac{e^{-\beta F''}}{e^{-\beta F'} + e^{-\beta F''}}. \qquad (14)$$

Measure of uncertainty of these preferences in the view of their entropy or a function on the basis of the entropy [2-7] allows us judging about the degree of conflictability of the operational situation. Parameters and threshold values of the entropy give us a tool for more effective control in, for instance, this special case of EHSG operation.

**The problem solution.** After finding the forces and moments from the developed methods (1)-(9) for both types of EHSG, we may compare results and on their basis choose the operational mode that fits the required restrictions the best.

The combined mode of operation which is just a compilation of the considered before elementary ones is developed in the view of a conditional system of equations

$$F_{cn} = \begin{cases} F'', & \alpha < \alpha_0; \\ F', & \alpha = \alpha_0; \\ F''', & \alpha > \alpha_0, \end{cases} \qquad (15)$$

where $\alpha_0$ – angle of deflection of the ship's helm blade at which the corresponding hydro-cylinder it changes its-own mode of operation. Here, it is implied the change, let us say, for example, from retracting onto pushing out the rod and vice versa from pushing the rod out to pulling it back again.

This angle, for instance, for the given conditions (see fig. 2), is

$$\alpha_0 = \beta - arctg \frac{E}{A}. \qquad (16)$$

For interpretational purposes of the obtained results let us introduce a coefficient

$$k = \frac{F_{cn}}{F_c}, \qquad (17)$$

which is the ratio of the forces acting in the four-arm tiller EHSG equipped with the piston hydro-cylinders (see fig. 2) to the forces acting in the traditional plunger EHSG (see fig. 1).

**Practical application of the problem solution.** Let us consider, for example, a general cargo, universal, dry cargo vessel, DWT 13,500 t, the ship's speed 18.2 knots. The prototype-vessel, let us say, of the «Geroi Panfilovtsy» series. She is presumable equipped with the plunger EHSG of the steering engine builder's type of 4EP220, Stork (the Netherlands); the nominal moment equals 1,167 kNm [1].

Now, consider a possible assumed retrofitting with the replacement of the installed EHSG for the proposed improved four-arm tiller EHSG equipped with the piston hydro-cylinders type shown in fig. 2.

For the supposed approximate data given: $\alpha = 0 \ldots 35°$; $H = 0.6$ m; $C_n$ approximated with the expression

$$C_n = -6 \cdot 10^{-6}\alpha^4 + 0.0003\alpha^3 - 0.0043\alpha^2 + 0.0665\alpha + 0.0025; \qquad (18)$$

$k_k = 0.578$; $k_g = 2.015$; $\rho = 1{,}030$ kg/m$^3$; $v_0 = 18.2$ knots; $F = 24.375$ m$^2$; $C_d$ approximated with the expression

$$C_d = 4.86 \cdot 10^{-5}\alpha^2 + 3.01 \cdot 10^{-3}\alpha + 0.208; \qquad (19)$$

$b = 3.75$ m; $b_1 = 0.9375$ m; $r = 0.67$ m; $\beta = 20°$, $\gamma = 5°$; $A = 1.69$ m; $E = 0.135$ m; mathematical modeling by formulae (1)-(9), (15)-(19) demonstrates expediency of the four-arm tiller EHSG equipped with the piston hydro-cylinders application.

**The researches results.** The results of the modeling by formulae (1)-(9), (15), (16), (18), and (19) are illustrated in fig. 3.

As a result of the researches we see the advantages of the four-arm tiller EHSG equipped with the piston hydro-cylinders type shown in fig. 2. The ratio (17) is represented with its plot in fig. 4. In the absolute values, figuratively speaking, we lose for about 16.4 kN at 100 kN necessary, but gain 33.1 kN at 310 kN necessary instead (see fig. 3, 4).

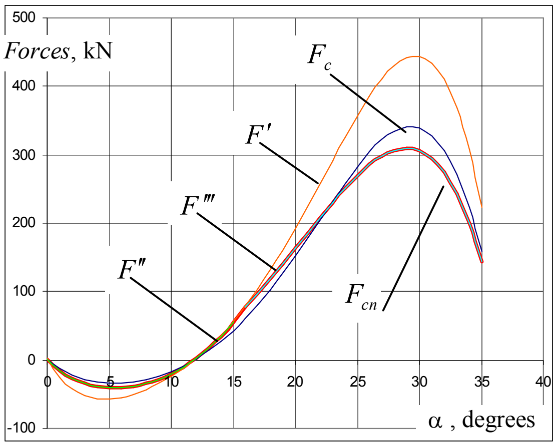


Figure 3 – Forces acting in the EHSG

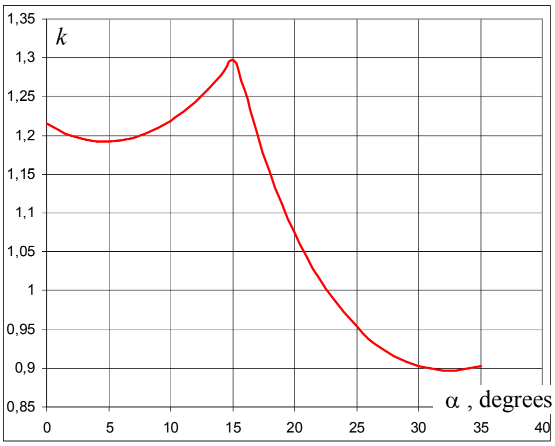


Figure 4 – Advantage of retrofitting the EHSG

As we can see from fig. 3 and 4, for assumed data, at the diapason of the greater angles of the helm deflection of about 30 … 35°, the advantage of the proposed retrofitted EHSG constitutes up to more than 10% by the force necessary for the same moment at the rudder. Although at the smaller angles of the helm deflection, approximately 0 … 17°, the disadvantage of the improved steering engine is between 20 … 30%, nevertheless the forces acting are about

10 times less than for the marginal angles. Thus, we observe the reduction of the maximal tensions.

**Conclusions.** Evidently, we might suppose that the stress in the EHSG may be decreased, therefore the mass of the installation can be reduced, reliability – raised.

**Prospects of further researches.** For further researches it is prospective to deal with the entropy paradigm in studying multi-alternativeness of operational situations on conditions of possible conflicts with the use of the methods (10)-(14).

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**Гончаренко А.В.** РАЦІОНАЛЬНІ РЕЖИМИ ЕКСПЛУАТАЦІЇ ЕЛЕКТРОГІДРАВЛІЧНОЇ РУЛЬОВОЇ МАШИНИ З ЧОТИРИПЛЕЧОВИМ РУМПЕЛЕМ З УРАХУВАННЯМ БАГАТОАЛЬТЕРНАТИВНОСТІ ТА ПЕРЕВАГ

*Досліджено доцільність застосування електрогідравлічної рульової машини з чотириплечовим румпелем, обладнаної поршневими гідроциліндрами, замість плунжерної 4ЕР220, Stork (Нідерланди), для суховантажного судна, 13500 т дедвейт, швидкість 18,2 вузла. Обґрунтування ефективності переобладнаної рульової машини виконано за допомогою належного математичного моделювання проілюстрованого відповідними графіками. Показано роль багатоальтернативності, переваг, ентропії та конфліктів у процесі експлуатаційного керування.*
*Ключові слова: електрогідравлічна рульова машина, суховантажне судно, суб'єктивний аналіз, суб'єктивна ентропія, індивідуальні переваги, багатоальтернативні ситуації, конфлікти переваг, канонічні розподіли, варіаційний принцип.*

**Гончаренко А.В.** РАЦИОНАЛЬНЫЕ РЕЖИМЫ ЭКСПЛУАТАЦИИ ЭЛЕКТРОГИДРАВЛИЧЕСКОЙ РУЛЕВОЙ МАШИНЫ С ЧЕТЫРЕХПЛЕЧЕВЫМ РУМПЕЛЕМ С УЧЕТОМ МНОГОАЛЬТЕРНАТИВНОСТИ И ПРЕДПОЧТЕНИЙ

*Исследована целесообразность применения электрогидравлической рулевой машины с четырехплечевым румпелем, оборудованной поршневыми гидроцилиндрами, вместо плунжерной 4ЕР220, Stork (Нидерланды), для сухогрузного судна, 13500 т дедвейт, скорость 18,2 узла. Обоснование эффективности переоборудованной рулевой машины выполнено с помощью должного математического моделирования проиллюстрированного соответствующими графиками. Показана роль много альтернативности, предпочтений, энтропии и конфликтов в процессе эксплуатационного управления.*
*Ключевые слова: электрогидравлическая рулевая машина, сухогрузное судно, субъективный анализ, субъективная энтропия, индивидуальные предпочтения, многоальтернативные ситуации, конфликты предпочтений, канонические распределения, вариационный принцип.*