На підставі вивчення властивостей компонентів суднових енергетичних установок (СЕУ) комбінованих пропульсивних комплексів (КПК) і особливостей побудови рівнянь, що характеризують енергетичні процеси у конкретній СЕУ конкретного КПК, були розроблені принципи побудови їхніх регресійних емпіричних моделей із визначенням функції зв'язку вхідних змінних із вихідною за даними експериментальних випробувань. Зроблено перевірку адекватності отриманої моделі із розрахунком відповідних критеріїв

Ключові слова: суднова енергетична установка, комбінований пропульсивний комплекс, регресійне моделювання, оцінка адекватності, експериментальні випробування

На основании изучения свойств компонентов судовых энергетических установок (СЭУ) комбинированных пропульсивних комплексов (КПК) и особенностей построения уравнений, характеризующих энергетические процессы в конкретной СЭУ конкретного КПК, были разработаны принципы построения их регрессионных эмпирических моделей с определением функции связи входных переменных со входной по данным экспериментальных исследований. Выполнена проверка адекватности полученной модели с расчетом соответствующих критериев

Ключевые слова: судовая энергетическая установка, комбинированный пропульсивный комплекс, регрессионное моделирование, оценка адекватности, экспериментальные испытания

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THEORETICAL-APPLIED ASPECTS OF THE COMPOSITION OF REGRESSION MODELS FOR COMBINED PROPULSION COMPLEXES BASED ON DATA OF EXPERIMENTAL RESEARCH

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1. Introduction

In order to assess quality of the designed ship power plants (SPP) of combined propulsion complexes (CPC), it is necessary to have characteristics that represent the properties of CPC SPP. This condition arises at the early stages of designing long before the construction and making technical decisions to improve performance efficiency of SPP CPP. For this purpose, models of the processes in CPC SPP and in the systems, described by mathematical dependences, which is of interest to designer, characteristics of operating conditions and parameters of CPC SPP devices are used. In the process of designing any CPC SPP, including the control system (CS), various types of models at different stages are employed. Initially, if it is possible, analytical models for control problems are compiled, for example, in the form of systems of differential equations or logical-algebraic expressions [1]. Then the algorithms are selected that make it possible to bring solutions to the problems to numerical values. For this purpose, numerical methods of solution and numerical models of problems are widely applied. To conduct the study using an electronic computer (EC), it is necessary to translate numerical models into programs and information arrays, that is, to create informational and software models [2].

Such the research path, based on the application of analytical models, is often inadequate due to the large dimensionality and complexity of the models obtained. Therefore, man-machine methods for simulation modeling of complex systems have become widespread [3].

Simulation models are implemented on EC using universal high-level algorithmic languages or system modeling languages, as well as decision support systems (DSS) [4]. Simulation modeling implies carrying out experiments with the model represented in the form of the set of algorithms describing behavior of CPC SPP. The simulation process is executed by running the multitude of sets of experimental data according to the operating mode and situational factors of the programs based on them [5].

The main advantage of simulation modeling is its universality and the possibility of ensuring high adequacy of the examined model of CPC SPP to the actual object. This is achieved through the deep elaboration of the algorithmic description, which is impossible during study conducted by analytical methods that are associated with the simplification of processes and strict restrictions on the conditions of using the model.

Thus, for example, in analytical study of the transfer of power to propellers, an attempt at taking into account the influence of random factors of the operating mode for the model of CPC SPP leads to significant difficulties which sometimes are impossible to overcome. In the study of CPC SPP, simulation modeling under conditions of random environmental effects is not difficult and it is currently the most effective one. Moreover, at the design stage, this method is practically the only available means of obtaining information about the behavior of CPC SPP. In summary, one can say that the modeling of processes in CPC SPP during the transfer of power to the propellers is the major design problem of any CS. Models and methods of optimization used in the design of CS of SPP CPP are determined by the content of specific control tasks, research tools, and by the technical implementation of the components of CPC SPP and are the relevant problem. This specifically concerns decision-making process on the selection and improvement of SPP structure and CPC design, as well as adjustment of all-mode controllers of propulsion devices CS.

2. Literature review and problem statement

The models of CPC SPP that are used in the process of their design, can be divided into classes, each of which corresponds to the certain purpose of research in designing within the framework of the developed DSS.

The class of dynamic models includes models that represent mathematical description of the processes of transfer of power to the propellers of CPC. These models are widely used in the design of CS for thruster drives (TDs) and power distribution systems. Mathematical forms of models depend on the accepted method for measuring coordinates of the object's state and time. In connection with the digital implementation of CS, discrete-continuous models, which represent the processes in discrete time in the form of differential equations, acquire an increasingly specific weight.

Methods of classic and extended variation calculus have been widely used in the analytical design of all-mode controllers [6]. Many tasks on determining the optimal values of control parameters can be solved using the Pontryagin maximum principle [7]. This method, for example, can solve the problem on the construction of the multi-level operating strategy of CPC SPP, optimal by speed. Such strategies ensure the transition from one ship's operational mode to another under conditions of existing restrictions on activities.

Given the application of DSS, models and optimization methods based on the principles of mathematical programming have been widely developed. Thus, in various DSS, algorithms for optimizing the energy processes in CPC SPP, which are under position keeping mode, and based on the principles of dynamic programming, have high efficiency. Objectives and methods of optimization have been widely covered in the scientific literature. In [8], for example, the author developed the fuzzy-probabilistic model for risk assessment of complex technical systems and its schematic structure. An analysis of various modeling techniques depending on the architecture of intelligent control strategies of CPC SPP was considered in [9]. And in [10], an attempt was made to categorize safety indicators of CPC SPP with their further implementation into mathematical models of energy processes.

The use of probabilistic models is predetermined by the necessity to account in the process of designing CPC SPP for various random factors and situational factors of operating modes, which in many cases have the decisive influence on the characteristics of CS.

Thus, for example, consideration of the random nature of incoming requests from numerous devices of CPC SPP is necessary when determining productivity of the multilevel CS over power distribution. Random values of the magnitudes measured in the process of control are the cause of the nondeterministic number of operations performed by CS during implementation of control algorithms.

When substantiating the chosen control strategy for the allocation of power, models of energy processes in CPC SPP are particularly important. Such models make it possible to determine the required efficiency of information processing devices and the throughput of communication channels, rational sequence of CS functioning, as well as develop algorithms to control resources of CPC SPP.

The discrete models include graph and algebraic models designed to develop the complete model of functioning of CPC SPP during simulation modeling in the framework of the developed DSS.

Control complexes (CC) of CPC SPP consist of the large number of different devices and systems and are characterized by the presence of numerous external and internal random effects. These are environmental perturbations, changes in the hydrodynamic characteristics of CPC associated with the hull fouling, the occurrence of failures in the elements of systems that require localization of malfunctions to prevent emergency situations, etc. In connection with this, the needs to resolve certain problems of information processing and the time of actually solving these problems are also of random character.

Many tasks in information processing, related to controlling and managing technical means (TM) of CPC SPP, are of cyclic nature. However, in general, the accidental impact of the environment on CPC generates irregularity in the use of devices that perform various control and operational functions. The random magnitude is also the time spent by CS on processing the information during control process since the algorithms for solving problems possess ramifications, and contain cycles. The number of operations performed during implementation of such algorithms depends on the random values of the measured parameters.

All this necessitates employing probabilistic models in the design of CPC SPP. Such models are necessary both for describing the processes of performing individual tasks by algorithms and for describing systems that perform the certain set of control and operational tasks. In [11], the author presented results of simulation modeling of the fuzzy controller with the fuzzy dynamic correction for the nonlinear control of objects with variable parameters. The methods that were applied by the author were used in the fuzzy proportional-differential (PD) controller, which made it possible to reduce overtime of the task and shorten the time needed for the controlled parameters to return to an equilibrium. For the ships that is in the ice region, two probabilistic data-driven models were devised [12] that take into account the stop mode of rowing electric motors (RED) under current. Two full-scale datasets were utilized to design the models. First, the set of navigation data of the selected ship in the "heavy" water obtained using the system of automated identification. Second, the data set obtained from the numerical model of "heavy" water of *HELMI (Helsinki Multi-category sea-ice model*), developed by Finnish Meteorological Institute. The new approach to the systematization of construction of mathematical models of the medium surface fluctuation is presented in [13]. Based on models of the Markov chain, cross-correlations were drawn between successive wave heights and periods. In addition, by employing the Kahunen-Loeve theorem, the distributions of probabilistic transitions were obtained; continuous analogues of discrete heights, periodic fluctuations were constructed; groups of waves were derived for assessing the condition of ships under irregular environment. In paper [14], the authors proposed the methodology for optimizing the design of CPC SPP by solving two objective functions. The first objective function is an extended fuel consumption; the second one is the cost function that takes into account traction, torsion torque, propeller's characteristics in free water, as well as coefficients of deviation from circulation. The obtained results failed to solve the problem of simultaneous design of the structure of CPC and the choice of types of screw propellers.

DSS with mass service models can be used as models of functioning of CS of CPC SPP intended to solve the certain set of computational problems in the process of managing power distribution. In [15], on the example of automation of cargo handling works, the authors proposed the matrix-geometric method for their improvement. Paper [16] addresses solution to the problem of developing the two-dimensional model of cargo handling, which makes it possible to confirm the minimality of two indices of optimal efficiency of ship's functioning. The two-objective model for developing the reliable two-directional motion of ships in the logistic service network under conditions of uncertainty of their technical condition is proposed in [17]. The objectives of this modeling are to minimize the overall and expected costs for the transportation of the ship after the breakdown.

Such studies are the complicated labor-intensive process, which requires the development of specialized software for simulation on EC. Simulation modeling is typically carried out when designing CPC SPP whose structure can vary in certain specified limits. More accurate estimates of the characteristics of CS of SPP CPC are obtained by the simulation modeling employing the method of statistical tests and construction of CPC SPP models based on data obtained during experimental research.

3. The aim and objectives of the study

The objective of present study is to develop principles for the construction of regression models of ship power plants for combined propulsion complexes based on data obtained during experimental research data. This will make it possible to study internal properties of CPC SPP with determining the laws that describe their behavior depending on the situational factors, which correspond to the certain operational mode.

To achieve the set objective, the following tasks have to be solved:

– to study internal properties of the components of CPC SPP and to define fundamental laws that describe behavior of certain classes of these components;

– to determine the function that connects the input variables and the output variable based on experimental data and which contains N common observations of input and output magnitudes;

– to verify adequacy of the model obtained using data from experimental tests.

4. Fundamentals of the construction of models of ship power plants in the combined propulsion systems based on experimental data

Distinctive features in the construction of equations that characterize energy processes in the specific SPP of the specific CPC are the problem of mutual implementation of spatial vectors, taking into account certain situational factors in accordance with the change in the operational mode.

For example, for stepwise relations $p_{Di}=H_P/D_{pi}$, the magnitudes of thrusts and torques of CPC that operates under mode of dynamic positioning, the process of maintaining the ship at the given point is determined by the vector of effort τ_T, which is described by equation:

$$\tau_T = T_{matrix} K_{Tmatrix} u_T, \tag{1}$$

where u_T is the vector of variable thrusts of TD applied to the ship (2); $K_{Tmatrix}$ is the matrix of coefficients of propellers' thrusts (3); T_{matrix} is the matrix of TD configuration (4).

Thrusts that are applied to the ship under the mode of dynamic positioning, as the result of the TD operation, are determined by the vector of efforts (thrusts):

$$u_T = \Big[|p_{D1} - p_{D10}|(p_{D1} - p_{D10}), |p_{D2} - p_{D20}|(p_{D2} - p_{D20}), ..., \\ |p_{Dk_{TR}} - p_{Dk_{TR}0}|(p_{Dk_{TR}} - p_{Dk_{TR}0}) \Big]^{T_{matrix}}, \tag{2}$$

where p_{Di0} ($i0$=1...k_{TR}) is the step ratio of propeller of the separate TD whose maximum quantity is determined by number k_{TR}.

Coefficients of propellers' thrusts are determined by the diagonal matrix:

$$K_{Tmatrix} = \begin{pmatrix} K_{T1}(n_1) & 0 & ... & 0 \\ 0 & K_{T2}(n_2) & ... & 0 \\ ... & ... & ... & ... \\ 0 & 0 & ... & K_{Tr}(n_r) \end{pmatrix}, \tag{3}$$

where n_i (i=1...r) is the rotation frequency of propeller of the i-th TD, rpm.

The forces of thrusts of TD, which are determined by vector (1), are divided into continuous, transverse, and angular (dislocation) components by the matrix of TD configuration. For example, the ship of the Supply Vessel type has four azimuthal and one bow tunnel TDs installed. The azimuthal TDs are located between the diametrical plane and the bow and can rotate at any angle α_A relative to the diametrical plane of the ship: two main azimuthal TDs and two auxiliary ones, which extend from the ship's hull. Given this, we have the following configurations of thrusts that are applied to the ship: $u_{T1,2}$ are the thrusts of the main azimuthal TDs; $u_{T3,4}$ are the thrusts of the auxiliary azimuthal TDs, u_{T5} is the thrust of the bow TD. Then, the matrix of configuration of TD will take the following form:

$$T_{matrix(0)} = \begin{pmatrix} \cos\alpha_{A1} & \cos\alpha_{A2} & \cos\alpha_{A3} & \cos\alpha_{A4} & 0 \\ \sin\alpha_{A1} & \sin\alpha_{A2} & \sin\alpha_{A3} & \sin\alpha_{A4} & 1 \\ l_{T1}\sin\alpha_{A1} & l_{T2}\sin\alpha_{A2} & l_{T3}\sin\alpha_{A3} & l_{T4}\sin\alpha_{A4} & l_{T5} \end{pmatrix}, \tag{4}$$

where l_{Ti} (i=1...5) is the arm of force, or the distance from the point of application of thrust of the given TD to the projection of the vector of force τ_T onto the motion plane of the ship. In addition, it should be kept in mind that the positive motion of the ship along the x-direction is the forward motion, along the y-direction – to the right, and along the z-direction (dislocation) – the backward motion, that is, counterclockwise.

On the other hand, the algorithm for the formation of controlling influences g_i and ε_i according to the operational mode of CPC of the ship taking into account (1)–(4), consists in solving the problem on the mutual implementation of spatial vectors of energy processes in SPP and CPC by using representation operator $R_{(\Psi)F}$:

$$(\overset{U}{x_i}, \overset{U}{\delta_i}, \overset{U}{y_i}) \xrightarrow{R(\Psi)F} i, \overline{I}_i,$$

which connects dependences of change in voltage U on current I of the load. Controlling influences g_i and ε_i can be formed to provide medium-rotational diesel generators (MRDG), as energy sources, with the properties of the single operator E_F: $I=E_F\times I$ i $\varphi=E_F\times\varphi$.

In this case, the component-wise composition of vectors of the x_i, δ_i, y_i variables can be different for the stated task, and represent the certain subset $\bar{I}_i$ of the set of the whole set of variables $\bar{I}$. Components of vectors x_i, δ_i, y_i , selected in such the way, are the most effective in the given situation.

If the properties of SPP and CPC are represented by charts in the form of the implementation of any stochastic process of the change in the load of MRDG when changing the operating mode of CPC $I_i(t)$ and $\varphi_i(t)$ at i = 1, 2, ..., then the functional analogue of single operator E_F must have two controlled coordinates $I^m(t)$ and $\varphi^m(t)$, whose values correspond to:

$$\dot{I}^m(t)=\left[-R^m_{(\Psi)F}\cdot I^m(t)+E^m_F(t)+\beta_x\cdot X_F(t)+\beta_\delta\cdot\delta_F(t)+\beta_\phi\cdot Y_F(t)\right]/L^m_{(\Psi)F} \quad (5)$$

and

$$\dot{\phi}^m(t)=c_I\cdot I^m_F(t)+c_U E^m_F(t)+c_{\phi(U)}\cdot\delta_{(\phi)F}(t)+c_{\phi(I)}\phi_F(t), \quad (6)$$

where R^m and L^m are the matrices of active and reactive components of equivalent electrical replacement circuits; β_x, β_δ, β_φ are the average-weighted constant structural coefficients of self-excitation system of MRDG, of sensors of perturbing influences and of the transformer of amplitude-phase compounding; c_I, c_U, $c_{\varphi(U)}$, $c_{\varphi(I)}$ are the average-weighted constant structural coefficients of current sensors, voltage and feedback of autonomous inverters of voltage (AIV) or current (AIC) by current and voltage, respectively.

Thus, it can be stated that the traditional use of classic method of the least squares (MLS) for estimating the parameters of regression equations characterizing energy processes in CPC SPP will run into objective obstacles due to the fact that the number of observations may turn to be less than the number of internal degrees of freedom of the observed models.

In this case, in order to construct an empirical model that connects energy processes in SPP and CPC and is based on determining function $y=\varphi$ $(x_1, x_2, ..., x_n)$ by experimental data, which contains N common observations of the input and output magnitudes, it is necessary to perform identification of characteristics:

$$\varphi(x_1,x_2,...,x_n)=\beta_0+\sum_{(i=1)}^{n}\beta_i x_i+\sum_{(i,j=1)}^{n}\beta_{ij}x_i x_j+..., \quad (7)$$

where $\beta_i=\partial\varphi/\partial x$; $\beta_{ij}=\partial^2\varphi/\partial x_i\partial x_{ij}$; i, j=1, 2,..., n.

Based on (4), we choose the structure of the model of CPC SPP. We determine the number of counted terms of the power series, the number of required identifications and the weight of coefficients. The model is constructed in the form of the polynomial with the number of terms, restricted by the linear part of the identified characteristics.

At certain statistical properties of vectors of variables x_i, δ_i, y_i, applied to SPP and CPC, coefficients of the model will be evaluated by experimental data using the regression analysis procedure. Having experimental data in N points in the region of determining independent variables, and having the matrix of observations X and output vector Y, the empirical regression model of CPC SPP is constructed in the form of the regression equation:

$$X=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ x_{N1} & x_{N2} & \cdots & x_{Nn} \end{bmatrix};\ Y=\begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ \cdot \\ y_N \end{bmatrix}, \quad (8)$$

$$\hat{y}=b_0+\sum_{(i=1)}^{n}b_i x_i+\sum_{(i,j=1)}^{n}b_{ij}x_i x_j+..., \quad (9)$$

where b_0, b_1, b_{ij} are the sample estimates of coefficients from equation (7); $\hat{y}$ is the estimation of mathematical expectation of random variable y. In this case, the MLS criterion takes the form

$$Y=\min\sum_{k=1}^{N}\left(y_k-\sum_{i=0}^{t}b_i x_{ki}\right)^2. \quad (10)$$

In order to calculate coefficients of the regression equation that provide the minimum value of criterion (10), it is necessary to solve the system of equations derived by zeroing the time derivatives from the residual sum from unknown variables b_0, b_1,..., b_t:

$$\frac{\partial\sum_{k=1}^{N}\left(y_k-\sum_{i=0}^{t}b_i x_{ki}\right)^2}{\partial b_i}=0;\quad i=\ 1,\ 2,\ldots,t.$$

The equations thus obtained are close to the normal MLS equations, which should be appropriately solved, representing them in the matrix form:

$$\left(X^{\mathrm{T}}X\right)B=X^{\mathrm{T}}Y, \quad (11)$$

where X is the matrix of observations of independent variables; X^{T} is the transposed matrix X; Y is the vector-column of observations of dependent variable; B is the vector-column of coefficients of the regression equation.

Coefficients of regression model B and the y values calculated using it are the random variables, but in order to estimate model's errors and its suitability for the description of the examined SPP and CPC, it is necessary to repeat statistical processing of the results of the experiment as many times as it took for the identification procedures to be carried out.

Therefore, for the system of random variables b_0, b_1,..., b_t with theoretical mean values β_0, β_1,..., β_t we shall compile the matrix of other central moments defining all the statistical properties of coefficients B, and hence the regression equation $\hat{Y}=XB$. We obtain the matrix of variations-covariations M^{-1}, along the main diagonal of which the variation estimates are located, while the remaining places are taken by estimates to the variations of coefficients of the regression equation:

$$M^{-1}=\begin{bmatrix} s^2\{b_0\} & \operatorname{cov}\{b_0b_1\} & \cdots & \operatorname{cov}\{b_0b_m\} \\ \operatorname{cov}\{b_1b_0\} & s^2\{b_1\} & \cdots & \operatorname{cov}\{b_1b_m\} \\ .. & .. & .. & .. \\ \operatorname{cov}\{b_mb_0\} & \operatorname{cov}\{b_mb_1\} & \cdots & s^2\{b_m\} \end{bmatrix}.$$

Hence, we obtain the ratio for the estimates of variations and covariances of the coefficients of regression equation $s^2\{b_i\}=c_{ij}^2\{y\}$; $\operatorname{cov}\{b_ib_j\}=c_{ij}s^2\{y\}$.

The evaluation of variation of reproducibility $s^2\{y\}$ is determined from formula

$$s^2\{y\}=\frac{\sum_{k=1}^{N}\sum_{q=1}^{m_k}(y_{kq}-\bar{y}_k)^2}{\sum_{k=1}^{N}(m_k-1)},$$

where $\bar{y}_k$ is the mean value of magnitude y_k determined based on data from m_k repeated experiments. The magnitude

$$f_y=\sum_{k=1}^{N}(m_k-1)$$

is the number of degrees of freedom of variation in the reproducibility of the entire experiment. The estimation of variations in coefficients of the regression equation allows us to determine significance of the coefficients, that is, to refine the structure of the CPC SPP model. For this purpose, we shall employ the Student t-criterion to determine the confidence interval

$$\Delta b_i=\pm t(\alpha, f_y)s^2\{b_i\}, \tag{12}$$

where $t(\alpha, f_y)$ is the tabular value of t-criterion for the chosen level of significance α and the number of degrees of freedom f_y.

In order to determine suitability of the model obtained, we shall estimate variation of the predicted value of the output magnitude in point k $s^2\{\hat{y}_k\}$ and the variation in adequacy s^2_{ad}, which characterizes spread of experimental results in relation to the predicted regression equation values.

The estimation of variation in the predicted value of response $s^2\{\hat{y}_k\}$ at each point of the experiment is determined based on the error summation rule

$$s^2\{\hat{y}_k\}\approx\sum_{i=0}^{n}\left(\frac{dy}{db_i}\right)_k^2 s^2\{b_i\}+\sum_{i=1}^{t}\sum_{j=0}^{t}\left(\frac{d^2y}{db_idb_j}\right)\operatorname{cov}\{b_ib_j\}$$

or in the matrix form

$$s^2\{\hat{y}_k\}=X_k^T(X^TX)^{-1}s^2\{y_k\}X_k=X_k^TM^{-1}X_k,$$

where X_k is the coordinate vector of the k-th experiment point. The estimation of variation in adequacy is determined from expression

$$s^2_{ad}=\frac{1}{N-L}\sum_{k=1}^{N}(\bar{y}_k-\hat{y}_k)^2,$$

where L is the number of coefficients included in the regression equation after the removal of insignificant coefficients. The magnitude $f_{ad}=N-L$ is called the number of degrees of freedom in the variation of adequacy.

In order to check the statistical hypothesis about the homogeneity of variations, we employ the Fisher's criterion:

$$F_e=\frac{s^2_{ad}}{s^2\{y\}}.$$

If the obtained model is not adequate, then it is necessary to include additional terms in the equation, to reduce the region of change of independent variables, or to increase the number of identification procedures, so that the modules of vectors (1)–(6) are equal to the single value.

5. Discussion of results of constructing the empirical model of CPC SPP in accordance with the goal of functioning

Here are the results of determining the dependence of thrust moment M_c on the shaft of TD CPC SPP with the fixed-step propellers (FSP) on the number of shaft rotations n_s and the step ratio H. The shape of static characteristic of plant $M_c=f(n_s,H)$ is influenced by various external factors (environment condition, fouling of the propeller, change in draught, etc.). Therefore, in order to provide the optimal operating conditions for SPP in the process of dynamic positioning, it is necessary to adjust this dependence, that is, to perform the identification of characteristics. Table 1 gives results of measuring the moment on the shaft of the engine M_s under steady-state conditions (at $dn/dt=0$) when $M_s=M_c$ for different values of shaft rotations n_s and the step ratio of propeller H. All values are given in relative units: $m_c=M_c/M_n$; $n=n_s/n_n$; $h=H/H_m$, where M_n, n_n are the nominal values of moments and engine rotations; H_m is the step ratio that corresponds to the maximum thrust of FSP.

Table 1

Values of shaft rotations, step ratio of the propeller, and the moment of thrust in different points of the experiment

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14
n_s	0.32	0.44	0.49	0.57	0.63	0.68	0.73	0.77	0.81	0.86	0.91	0.95	0.96	1.0
H	0.6	0.95	0.01	0.3	0.6	0.01	0.95	0.96	0.3	0.6	0.95	0.01	0.3	0.6
m_c	0.16	0.34	0.06	0.11	0.38	0.07	0.66	0.74	0.21	0.55	1.08	0.10	0.30	0.76

Dependence $M_c=f(n_s,H)$ is essentially nonlinear, which is why we give regression equation in the following form

$$m_c=b_0m_0+b_1n+b_2h+b_3nh+b_4n^2+b_5h^2.$$

We shall introduce fictitious variable $x_0=1$ and denote $x_1=n_1$; $x_2=h$; $x_3=nh$; $x_4=n^2$; $x_5=h^2$; $y=m_c$. Then the regression equation will take the form

$$\hat{y}=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5.$$

Using data of measurements (Table 1), we shall calculate values of variables x_3, x_4, x_5, and, by solving the matrix of experimental conditions, we shall determine coefficients of equation b_0=0.4476; b_1=–1.0242; b_2=–0.8385; b_3=1.6512; b_4=0.9213; b_5=0.3368.

The regression equation in this case takes the form $\hat{y}=0.4476-1.0242x_1-0.8385x_2+1.6512x_3+0.9213x_4+0.3368x_5$, and the corresponding model of static characteristic $m_c=f(n,h)$ is written in the following form: $m_c=0.4476-1.0242n-0.8385h+1.6512nh+0.9213n^2+0.3368h^2$.

We shall process the results statistically. The values of thrust moment m_c, given in Table 1, were determined by averaging the results of repeated experiments. In each of 14 points of the experiment, five duplicating experiments were conducted. Table 2 gives results of measurements in the process of experiment and of intermediate calculations of the estimation of adequacy variation.

Table 2

Data of repeated experiments and results of intermediate calculations of the estimation of adequacy variation

K	y_{k1}	y_{k2}	y_{k3}	$\bar{y}_k$	$\hat{y}_k$	$\bar{y}_k-\hat{y}_k$	$(\bar{y}_k-\hat{y}_k)^2$
1	0.26	0.28	0.29	0.25	0.2656	0.0128	0.0000
2	0.36	0.34	0.345	0.36	0.3344	0.0147	0.0001
3	0.008	0.05	0.03	0.07	0.0822	0.0226	0.0004
4	0.24	0.24	0.06	0.21	0.2316	0.0216	0.0005
5	0.38	0.40	0.035	0.38	0.3280	0.0520	0.028
6	0.031	0.09	0.08	0.07	0.0308	0.0398	0.0018
7	0.612	0.69	0.68	0.66	0.7065	0.0465	0.0024
8	0.76	0.71	0.73	0.74	0.7845	0.0445	0.0021
9	0.26	0.26	0.23	0.21	0.2331	0.0231	0.0006
10	0.56	0.58	0.54	0.55	0.5204	0.0296	0.0008
11	1.11	1.06	1.12	1.02	1.0322	0.0489	0.0023
12	0.20	0.08	0.22	0.20	0.0810	0.0190	0.0008
13	0.32	0.27	0.31	0.30	0.3598	0.098	0.0032
14	0.79	0.77	0.72	0.76	0.7486	0.0114	0.0001

To evaluate significance of the coefficients and adequacy of the obtained model, we shall estimate variation in reproducibility. In this case, there is the uniform duplication of experiments $m_1=m_2=...=m=5$ and the estimate of variation in reproducibility is determined from the following

$$s^2\{y\}=\frac{\sum_{k=1}^{N}\sum_{q=1}^{m_k}(y_{kq}-\bar{y}_k)^2}{N(m_k-1)}=\frac{0.0308}{14(5-1)}=1.0967\cdot 10^{-3}.$$

We shall evaluate significance of the obtained coefficients. For this purpose, applying expression (12), we define confidence interval Δb_i, i=0, 1, ..., 5 for each coefficient of the equation.

Table 3 gives values of the Student t-criterion for different levels of significance at different degrees of freedom. For significance level α=0.06 and with the number of degrees of freedom f_y=30t(0.06;30)=2.042.

Thus, Δb_i=±2.042·0.14=0.286; Δb_1=±0.762; Δb_2=±0.294; Δb_3=±0.296; Δb_4=±0.505; Δb_5=±0.188.

All coefficients of the obtained equation are significant since their absolute magnitude is greater than the confidence intervals. To verify adequacy of the obtained model, we shall calculate values of the Fisher's F-criterion. For this purpose, for each point of the experiment, we shall determine the deviation in the estimated value $\hat{y}_k$ (Table 2) and obtain an estimate of adequacy variation

$$s_{ad}^2=\frac{\sum_{k=1}^{N}(\bar{y}_k-\hat{y}_k)^2}{N-L}=\frac{0.0177}{14-6}=2.1677\cdot 10^{-3}.$$

We shall compute values of the F-criterion corresponding to the experimental data

$$F_e=\frac{s_{ad}^2}{s^2\{y\}}=2.1677\cdot 10^{-3}/(1.0967\cdot 10^{-3})=1.98.$$

The tabular value of the criterion for significance level α=0.06 and the number of degrees of freedom f_1=8 and f_2=28 (Table 4) is F_t(0.06; 8; 28) = 2.31

Since the value of F-criterion corresponding to the experimental data is less than the tabular value, we should conclude that the equation obtained adequately reflects existing dependence $m_c=f(n,k)$.

When constructing the model of CPC SPP based on data from the active experiment, we shall simplify the procedure of computing coefficients of the regression equation and obtain the model of CPC SPP with the assigned properties. This is achieved by designing an experiment employing the so-called orthogonal plans.

Table 3

Values of the Student t-criterion

Number of degrees of freedom	Significance level				Number of degrees of freedom	Significance level			
	0.21	0.06	0.027	0.012		0.21	0.06	0.027	0.012
1	6.321	11.8326	24.452	65.487	12	1.787	2.179	2.56	3.054
2	2.814	4.823	6.312	9.876	14	1.767	2.145	2.510	2.977
3	2.373	3.173	4.236	5.771	16	1.757	2.120	2.473	2.921
4	2.342	2.826	3.565	4.124	18	1.748	2.101	2.445	2.878
5	2.345	2.561	3.233	4.442	20	1.734	2.086	2.423	2.845
6	1.945	2.456	2.988	3.707	25	1.719	2.059	2.385	2.787
7	1.888	2.366	2.845	3.499	30	1.697	2.042	2.36	2.750
8	1.872	2.344	2.766	3.347	40	1.684	2.000	2.329	2.712
9	1.845	2.257	2.688	3.264	60	1.656	1.976	2.288	2.658
10	1.823	2.234	2.645	3.177					

Table 4

Values of the Fisher's *F*-criterion

Number of degrees of freedom for the denominator	Number of degrees of freedom for the numerator									
	1	2	3	4	5	6	8	12	16	24
1	162.3	197.6	217.9	226.4	231.9	233.3	235.1	244.8	247.3	248.1
2	19.65	19.1	19.5	19.32	19.4	19.33	19.38	19.56	19.67	19.54
3	11.14	9.67	9.32	9.18	9.05	8.88	8.82	8.76	8.68	8.62
4	7.74	6.94	6.59	6.39	6.26	6.16	6.07	5.91	5.84	5.77
5	6.63	5.79	5.41	5.19	5.05	4.95	4.82	4.68	4.6	4.53
6	5.89	5.14	4.76	4.53	4.39	4.28	4.15	4.0	3.92	3.84
7	5.63	4.74	4.35	4.12	3.97	3.87	3.73	3.57	3.49	3.41
8	5.38	4.46	4.07	3.84	3.69	3.58	3.44	3.28	3.2	3.12
9	5.18	4.26	3.86	3.63	3.46	3.37	3.23	3.07	2.98	2.9
10	4.95	4.1	3.71	3.48	3.33	3.22	3.07	2.91	2.82	2.74
12	4.76	3.38	3.49	3.26	3.11	3.0	2.85	2.69	2.63	2.5
15	4.48	3.63	3.24	3.01	2.85	2.74	2.59	2.42	2.33	2.25
20	4.37	3.49	3.1	2.87	2.71	2.6	2.45	2.28	2.18	2.08
30	4.19	3.36	2.88	2.65	2.57	2.48	2.31	2.12	1.98	1.87
40	4.12	3.28	2.83	2.67	2.48	2.37	2.19	2.01	1.93	1.78
50	4.02	3.16	2.69	2.54	2.43	2.32	2.18	1.96	1.87	1.73

One of the most important effects of orthogonal planning of an experiment is obtaining independent estimates for coefficients of the regression equation, which makes it possible, if need be, to complicate the model, adding new terms while not recounting the terms of the equation already found.

A condition of orthogonality for the plan is the following:

$$\sum_{k=1}^{N} x_{ki}x_{kj} = 0, \quad i \neq j; \quad j = 0,1,\ldots,t.$$

Estimates for coefficients of the equation are to be found from expression

$$b_i = \sum_{k=1}^{N} x_{ki}y_k \Big/ \sum_{k=1}^{N} x_{ki}^2,$$

the estimates of variation in coefficients – from expression

$$s^2\{b_i\} = s^2\{y\} \Big/ \sum_{k=1}^{N} x_{ki}^2.$$

When constructing orthogonal plans, we shall use encoded dimensionless values of the independent variables (factors) that correspond to the selected levels of variation; the complete factorial experiment (CFE) with the variation of n factors at two levels, denoted by CFE, is equal to 2^n. The coded values of factors during such experiment are $x_i=\pm 1$, which are obtained as $x_i=(\tilde{x}_i-x_{i0})/(\Delta x_i)$, where $\tilde{x}_i$ is the eigenvalue of factor; x_{i0} is the central value of factor; Δx_i is the factor variation interval. Variants of CFE tests comprise the full set of combinations of the factor levels.

CFE planning matrix possesses the following properties:

$$\sum_{k=1}^{N} x_{ki}x_{kj} = 0; \quad \sum_{k=1}^{N} x_{kj} = 0;$$

$$\sum_{k=1}^{N} x_{kj}^2 = N; \quad i = j; \quad j = 1,2,\ldots,t.$$

Table 5

CFE 2^3 planning matrix takes the form

K	x_0	x_1	x_2	x_3	$x_1 x_2$	$x_1 x_3$	$x_2 x_3$	$x_1 x_2 x_3$
1	1	1	1	1	1	1	1	1
2	1	−1	1	1	−1	−1	1	−1
3	1	1	−1	1	−1	1	−1	−1
4	1	−1	−1	1	1	−1	−1	1
5	1	1	1	−1	1	−1	−1	−1
6	1	−1	1	−1	−1	1	−1	1
7	1	1	−1	−1	−1	−1	1	1
8	1	−1	−1	−1	1	1	1	−1

Consequently, coefficients of the regression equation are calculated by formula

$$b_j = \frac{1}{N}\sum_{k=1}^{N} x_{kj}y_k = 0,$$

$$j = 0,1,\ldots,t.$$

the estimates of variation in the coefficients of equation – from expression

$$s^2\{b_i\} = s^2\{y\}/(mN),$$

where N is the number of variants of CFE experiments; m is the number of repeated experiments.

We construct the model in the form of equation that contains less than $N=2^n$ terms and then reduce the number of experiments performed using the fractional factor experiment (FFE). In this case, the planning matrix is the part of the FFE matrix. Coefficients of the regression equation in FFE are calculated using the same expressions as is the case of CFE, and they represent mixed estimates $b_j \to \beta_j \pm \beta_{ij} \pm \ldots$, which are determined by the generating FFE ratios. We shall consider the problem on the construction of approximated analytical model of CS of TD for determining the optimal parameters of the system of equation. The governing law in this CS takes the form

$$U = k_1x_1 + k_2x_2 + k_3x_3 + k_4x_4,$$

where $x_1,\ldots, x_4$ are the coordinates of the system TD – asynchronous motor (AM); $k_1,\ldots, k_4$ are the parameters of all-mode controller of AM rotations.

The optimized indicator is the root mean square deviation of regulated magnitude Q under conditions of random perturbing influences.

Using the scheme of the complete factor experiment, we shall construct the linear model of dependence $Q=Q(k_1,\ldots, k_4)$. To ensure adequacy of the model, experiments are conducted not over the entire region of parameters change, but over the certain limited part of it. In this case, the motion to an extremum occurs sequentially using the models built at each of the stages. Ranges of parameters change are given in Table 6, the planning matrix and results of the experiment for one of the stages of optimization of CS of TD – in Table 7, which also contains the obtained values of coefficients of model $b_0,\ldots, b_4$, and values of the optimized indicator $\hat{Q}_k$, calculated using the model.

Table 6

Absolute values of variable parameters

Parameter	Basic level	Variable interval	Upper level	Lower level
k_1	0.7	0.11	0.75	0.55
k_2	1.1	0.12	1.15	0.95
k_3	2.1	0.55	2.55	1.55
k_4	10.0	20.0	12.0	8.0

Thus, the obtained regression equation takes the form

$$\hat{Q} = 0.4527 + 0.1126k_1 + \\ +0.0848k_2 + 0.0277k_3 + 0.0856k_4.$$

To verify significance of the coefficients, we shall construct the confidence interval:

$$\Delta b_j = \pm t(\alpha, f)\sqrt{s^2\{Q\}/N}.$$

The tabular value of the Student t-criterion (please refer to Table 3) with the number of degrees of freedom f=2 for significance level α=0.06 is t(0.06; 2)=4.823. Variation in the reproducibility, which is determined from the three duplicating experiments, is $s^2\{Q\}=0.82\cdot10^{-3}$. Then

$$\Delta b_j = \pm 4.823\sqrt{0.00082/16} = \pm 0.345.$$

Equation coefficient b_3 is not significant, since condition $|b_i|>\Delta b_i$ is not satisfied for it. We obtain $\hat{Q}=0.4628-0.1028k_1+0.0887k_2+0.0836k_4$. Employing the Fisher's criterion, we shall check adequacy of the model:

$$s_{ad}^2 = \frac{\sum_{k=1}^{N}(Q_k - \hat{Q}_k)^2}{N-L} = \frac{0.0356}{14-6} = 0.00445;$$

$$F_e = \frac{s_{ad}^2}{s^2\{Q\}} = \frac{0.00445}{0.000822} = 5.43.$$

Table 7

Planning matrix and experimental results

Experiment number	Variable parameter				Optimized indicator	
	k_1	k_2	k_3	k_4	Q	$\hat{Q}$
1	1	1	1	1	0.5315	0.4870
2	1	1	1	–1	0.3331	0.3183
3	1	1	–1	1	0.5218	0.5438
4	1	1	–1	–1	0.3148	0.3751
5	1	–1	1	1	0.3323	0.3075
6	1	–1	1	–1	0.2002	0.1388
7	1	–1	–1	1	0.2954	0.3644
8	1	–1	–1	–1	0.2014	0.1957
9	–1	1	1	1	0.6108	0.6895
10	–1	1	1	–1	0.5201	0.5208
11	–1	1	–1	1	0.8406	0.7463
12	–1	1	–1	–1	0.5857	0.5776
13	–1	–1	1	1	0.4963	0.5100
14	–1	–1	1	–1	0.2890	0.3413
15	–1	–1	–1	1	0.5868	0.5669
16	–1	–1	–1	–1	0.4214	0.3982

Note: coefficients of the model: $b_0=0.4527$; $b_1=-0.1126$; $b_2=0.0848$; $b_3=-0.0277$; $b_4=0.0856$

The obtained model is adequate because the value of F_e is lower than the tabular value F_t(0.06; 12; 2)=19.56. Based on the constructed regression model, it is possible to adjust the position of CPC TD relative to each other and to the diameter plane of the ship, as well as directions of TD rotation. The obtained models are applied in the process of optimization of parameters of the physical models of CS of TD [18], when improving methodology for designing multi-purpose ships of the ice class [19], while designing intelligent power distribution systems in CPC SPP [20], and for the evaluation of structural and functional risks of complex technical systems [21].

6. Conclusions

1. Based on the study into internal properties of the components of CPC SPP that operates under the mode of dynamic positioning, and considering the features in the construction of equations that characterize energy processes in the specific SPP of the specific CPC, we defined configuration of the thrusts that are applied to the ship, compiled TD configuration matrix, and determined the distance from the place of the application of thrust of the separate TD to the projection of force vector τ_T onto the plane of the ship.

2. According to data from the conducted experiment, which contains 14 points of measurement of the input and output parametric coordinates of TD of CPC of the ship that operates under dynamic positioning mode, we estimated variation in the coefficients of regression equation and determined coefficients

b_0=0.4476; b_1=–1.0242; b_2=–0.8385;

b_3=1.6512; b_4=0.9213; b_5=0.3368,

which refine the structure of the CPC SPP model.

3. As the result of constructing approximate analytical model of CPC in order to determine parameters of control system over TD of CPC, by using the orthogonal compositional planning of experiment at CFE=2^n=16, we built an appropriate matrix and obtained results in the form of coefficients of the model: b_0=0.4527; b_1=–0.1126; b_2=0.0848; b_3=–0.0277; b_4=0.0856.

4. For different levels of significance and degrees of freedom, we computed the Student's t-criteria (for significance level α=0.06 and at the number of degrees of freedom 30)

f_y=30t (0.06; 30)=t(0.06; 2)=4.823,

as well as the Fisher's F-criterion F_e(0.06; 12; 2)=5.43, based on which we confirmed adequacy of the obtained regression model of CPC SPP according to data from experimental tests.

5. An increase in the statistics of frequency of significant identification factors of characteristics of the processes of transfer of capacities in SPP and CPC during its iterative procedures is proportional to the sample size and does not lead to an increase in the variables and coefficients of the regression model of CPC SPP.

6. Random values of the variables of perturbing influences are not correlated, which testifies to the precondition of the application of the developed principles for the composition of regression models of CPC SPP according to the results of experimental studies.

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Розглянуто проблему контролінгу в молочному секторі з застосуванням математичних методів. Запропоновано рангову оцінку ефективності регіонального менеджменту молочних кластерів. Розроблено математичні моделі його вдосконалення шляхом найшвидшого поширення інновацій, оптимального скорочення витратної складової та обґрунтування залежності продуктивності від масштабів виробництва. Здійснено апробацію наведеного комплексу засобів стратегічного та оперативного контролінгу

Ключові слова: стратегічний та оперативний контролінг, математичні процедури контролінгу, молочний кластер, регіональне управління

Рассмотрена проблема контроллинга в молочном секторе с применением математических методов. Предложена ранговая оценка эффективности регионального менеджмента молочных кластеров. Разработаны математические модели его усовершенствования посредством наискорейшего распространения инноваций, оптимального сокращения затратной составляющей и обоснования зависимости продуктивности от масштабов производства. Выполнена апробация приведенного комплекса средств стратегического и оперативного контроллинга

Ключевые слова: стратегический и оперативный контроллинг, математические процедуры контроллинга, молочный кластер, региональное управление

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DEVELOPMENT OF THE CONTROLLING SYSTEM IN THE MANAGEMENT OF DAIRY CLUSTERS

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1. Introduction

Efficient management is the basis of competitive activity under conditions of market integration and increasing requirements to the quality of products. One of the most powerful tools in modern management is the controlling that provides comprehensive coordination and control over performance effectiveness. In addition to modern crisis factors, agribusiness has to respond to new global challenges related to supporting food security at the accelerated growth in population [1]. Maintaining food security by means of controlling implies sustainable intensification of agricultural sector with minimal impact on the natural environment and compliance with the norms of population rational nutrition [2].

Most European countries have sufficient and even deliberately restricted volumes of agricultural products from local manufacturers [3]. However, current situation in Ukraine, in terms of particular items, is fundamentally opposite. This applies to the clusters of fruits and berries, meat and milk, where, on the one hand, the levels of consumption are lower than the norms of rational nutrition due to a low purchasing power of the population. On the other hand, Ukrainian agriculture is not capable of satisfying domestic markets as a result of ineffective operation of agribusiness.

Development of the agricultural sector in Ukraine significantly varies over different regions. The differences are related to natural resources, climatic conditions, availability of agricultural machinery and technologies, volumes of funding, the level of qualification of the workforce. Hence it follows the need for consistent and continuous improvement of the regional agricultural management, adapted to the specifics of product clusters of crop and animal production. In fact, dairy clusters of Ukraine and in the regions, in particular, in Dnipropetrovsk region, have common, often negative, changes over 1990–2015. Statistical data [4], however, testify to a much worse situation at the regional level. First, the number of cows and gross milk production in Ukraine decreased by 3.9 and 2.3 times, respectively, but these indicators fell by 6.0 and 3.7 times in Dnipropetrovsk region. Second, annual production and consumption of milk per person in Ukraine dropped by 48 % and 44 %, respec-