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 systematiza-
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 $p_{Di} = H_{Di} / D_{pi}$, 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 $\tau_T$, which is described by equation:

$$\tau_T = T_{matrix} K_{matrix} u_T,$$

(1)

where $u_T$ is the vector of variable thrusts of TD applied to the ship (2); $K_{matrix}$ 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):

$$u_T = \begin{pmatrix} p_{D1} - p_{D01} \\ p_{D2} - p_{D02} \\ \vdots \\ p_{Dn} - p_{D0n} \end{pmatrix},$$

(2)

where $p_{D0i} (i=0...kR)$ is the step ratio of propeller of the separate TD whose maximum quantity is determined by number $kR$.

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

$$K_{matrix} = \begin{pmatrix} K_{T1}(n_1) & 0 & \cdots & 0 \\ 0 & K_{T2}(n_2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & K_{Tk}(n_k) \end{pmatrix},$$

(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 $a_i$ 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 $u_{TD}$ are the thrusts of the main azimuthal TDs; $u_{TD1}$ are the thrusts of the auxiliary azimuthal TDs, $u_{TD5}$ is the thrust of the bow TD. Then, the matrix of configuration of TD will take the following form:

$$T_{matrix} = \begin{pmatrix} \cos \alpha_{a1} & \cos \alpha_{a2} & \cos \alpha_{a3} & \cos \alpha_{a4} & 0 \\ \sin \alpha_{a1} & \sin \alpha_{a2} & \sin \alpha_{a3} & \sin \alpha_{a4} & 1 \\ l_{T1} \sin \alpha_{a1} & l_{T2} \sin \alpha_{a2} & l_{T3} \sin \alpha_{a3} & l_{T4} \sin \alpha_{a4} & l_{T5} \end{pmatrix},$$

(4)

where $l_{T1} (i=1...5)$ 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 $\tau_y$ 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 $e_i$ 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 $R_{(y|x)}$:

$$\psi \in \psi \cup \kappa_{y|x} (x, \delta_x, y) \rightarrow i, t,$$

which connects dependences of change in voltage $U$ on current $I$ of the load. Controlling influences $g_i$ and $e_i$ can be formed to provide medium-rotational diesel generators (MRDG), as energy sources, with the properties of the single operator $E_i = E_{j} = I \varphi = E_{j} \varphi$. In this case, the component-wise composition of vectors of the $x_i, \delta_i, y_i$ variables can differ for the stated task, and represent the certain subset $I_i$ of the set of the whole set of variables $I$. Components of vectors $x_i, \delta_i, y_i$, selected in such a 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 $l_i(t)$ and $q_i(t)$ at $i = 1, 2, \ldots$, then the functional analogue of single operator $E_i$ must have two controlled coordinates $P(t)$ and $\phi(t)$, whose values correspond to:

$$I^* = \left[ -R_{y|x}^* - I^* + E_{y}^* + I \beta \cdot X_i(t) + \beta \Delta y_i + \beta Y_i(t) \right] / L_{y|x}^* \quad (5)$$

and

$$\phi^* = \phi + \beta \cdot X_i(t) + \beta \Delta y_i + \beta Y_i(t) \quad (6)$$

where $R^*$ and $L^*$ are the matrices of active and reactive components of equivalent electrical replacement circuits; $\beta$, $\beta$, $\beta$, are the average-weighted constant structural coefficients of self-excitation of MRDG, of sensors of perturbing influences and of the transformer of amplitude-phase compounding; $c_i, c_i, c_i, c_i$, 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 will fail to achieve the desired accuracy due to the fact that the number of observations may turn to be less than the number of independent variables.

In this case, in order to construct an empirical model that connects energy processes in SPP and CPC and is based on determining function (7), we shall compile the vector of random variables $y$ obtained in the process of statistical processing of the results of the experiment as many times as it took for the identification procedures to be carried out.

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 $x_i$, $y_i$, 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 matrix of observations $X$ and output vector $Y$, the empirical regression model of CPC SPP is constructed in the form of the regression equation:

$$y = \hat{b}_0 + \sum_{i=1}^{n} \hat{b}_i x_i + \sum_{j=1}^{n} \hat{b}_j x_j + \ldots$$

where $\hat{b}_0, \hat{b}_1, \hat{b}_2$ are the sample estimates of coefficients from equation (7); $y$ is the estimation of mathematical expectation of random variable $y$. In this case, the MLS criterion takes the form

$$E = \min_{\theta} \sum_{i=1}^{N} \left( y_i - \hat{b}_0 - \sum_{i=1}^{n} \hat{b}_i x_i \right)^2 \quad (10)$$

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 $b_0, b_1, \ldots, b_l$:

$$\frac{\partial}{\partial b_i} \sum_{i=1}^{N} \left( y_i - \hat{b}_0 - \sum_{i=1}^{n} \hat{b}_i x_i \right)^2 = 0; \quad i = 1, 2, \ldots, l.$$

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

$$(X^T X) \hat{B} = X^T Y$$

where $X$ is the matrix of observations of independent variables; $X^T$ is the transposed matrix; $Y$ 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 the 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 $b_0, b_1, \ldots, b_l$ with theoretical mean values $\beta_0, \beta_1, \ldots, \beta_l$ we shall compile the matrix of other central moments defining all the statistical
Control processes

properties of coefficients $B$, and hence the regression equation $Y=XB$. We obtain the matrix of variations-covariances $M^\dagger$, 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:

$$M^\dagger = 
\begin{bmatrix}
    s^2\{b_1\} & \text{cov}\{b_1,b_2\} & \ldots & \text{cov}\{b_1,b_n\} \\
    \text{cov}\{b_1,b_2\} & s^2\{b_2\} & \ldots & \text{cov}\{b_2,b_n\} \\
    \vdots & \vdots & \ddots & \vdots \\
    \text{cov}\{b_1,b_n\} & \text{cov}\{b_2,b_n\} & \ldots & s^2\{b_n\}
\end{bmatrix}.
$$

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

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

$$s^2\{y\} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{m} (y_{ij} - \bar{y})^2}{\sum_{p=1}^{m} (m_p - 1)},$$

where $\bar{y}_j$ is the mean value of magnitude $y_j$ determined based on data from $m_j$ repeated experiments. The magnitude

$$f_p = \frac{\sum_{i=1}^{N} (m_p - 1)}{
$$

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

$$\Delta b_i = t(a, f_p)s^2\{b_i\}, \quad (12)$$

where $t(a, f_p)$ is the tabular value of $t$-criterion for the chosen level of significance $a$ and the number of degrees of freedom $f_p$.

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

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

$$s^2\{\hat{y}_k\} = \sum_{i=1}^{n} \left( \frac{dy}{dt} \right)^2 s^2\{b_i\} + \sum_{i=1}^{n} \sum_{j=1}^{n} \left( \frac{dy}{dt} \frac{dy}{dt} \right) \text{cov}(b_i,b_j)$$

or in the matrix form

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

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

$$s^2\text{ad} = \frac{1}{N-L} \sum_{i=1}^{N} (\hat{y}_i - \bar{y}_i)^2,$$

where $L$ is the number of coefficients included in the regression equation after the removal of insignificant coefficients. The magnitude $f_{\text{ad}} = N - L$ 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:

$$F = \frac{s^2\text{ad}}{s^2\{y\}},$$

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 $M_t$ on the shaft of TD CPC SPP with the fixed-step propellers (FSP) on the number of shaft rotations $n_i$ and the step ratio $H$. The shape of static characteristic of plant $M_t = f(n_i,H)$ 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 $M_t$ under steady-state conditions (at $dn/dt=0$) when $M_t = M_{n_i}$ for different values of shaft rotations $n_i$ and the step ratio of propeller $H$. All values are given in relative units: $M_{0.025}/M_{0.25}; n=n_i/n_0; H=H_0/H_0$, where $M_{0.025}, n_0$ are the nominal values of moments and engine rotations; $H_0$ is the step ratio that corresponds to the maximum thrust of FSP.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_i$</td>
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<td>0.44</td>
<td>0.49</td>
<td>0.57</td>
<td>0.63</td>
<td>0.68</td>
<td>0.73</td>
<td>0.77</td>
<td>0.81</td>
<td>0.86</td>
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<td>0.96</td>
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<tr>
<td>$H$</td>
<td>0.6</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
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<tr>
<td>$m_0$</td>
<td>0.16</td>
<td>0.03</td>
<td>0.06</td>
<td>0.11</td>
<td>0.13</td>
<td>0.18</td>
<td>0.21</td>
<td>0.25</td>
<td>0.55</td>
<td>1.08</td>
<td>0.10</td>
<td>0.30</td>
<td>0.76</td>
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</table>

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

$$m = b_0m_0 + b_1n + b_2nH + b_3n^2 + b_4H^2.$$  

We shall introduce fictitious variable $x_0=1$ and denote $x_1=n; x_2=nH; x_3=n^2; x_4=H^2; y=m$. Then the regression equation will take the form

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5.$$
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 \(y=-0.4476-1.0242x_1-0.8385x_2+1.6512x_3+0.9213x_4+0.3368x_5\), and the corresponding model of static characteristic \(m_{ij}=m(n,n)\) is written in the following form: \(m_{ij}=m_0+0.4476-1.0242n-0.8385h+1.6512hn+0.9213n^2+0.3368hn^2\).

We shall process the results statistically. The values of thrust moment \(m_i\), 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

<table>
<thead>
<tr>
<th>(K)</th>
<th>(y_1)</th>
<th>(y_2)</th>
<th>(y_3)</th>
<th>(y_4)</th>
<th>(y_5)</th>
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</tbody>
</table>

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

\[
s^2\{y\} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{m} (y_{ij} - \overline{y})^2}{N(m-1)} = \frac{0.0308}{14(5-1)} = 1.0967 \times 10^{-3}.
\]

We shall evaluate significance of the obtained coefficients. For this purpose, applying expression (12), we define confidence interval \(\Delta b_j=0.1, ..., 5\) 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 \(\alpha=0.06\) and with the number of degrees of freedom \(f_j=28\), we have \(\Delta b_j=2.042.0.14=0.286; \Delta b_1=0.762; \Delta b_2=0.294; \Delta b_3=0.92; \Delta b_4=0.505; \Delta b_5=0.188\).

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 \(\overline{y}\) (Table 2) and obtain an estimate of adequacy variation

\[
s^2\{y\} = \frac{\sum_{i=1}^{N} (\overline{y}_i - \overline{y})^2}{N-L} = \frac{0.0177}{14-6} = 2.1677 \times 10^{-3}.
\]

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

\[
F = \frac{s^2\{y\}}{s^2\{y\}} = 2.1677 \times 10^{-3}/(0.0967 \times 10^{-3}) = 1.98.
\]

The tabular value of the criterion for significance level \(\alpha=0.06\) and the number of degrees of freedom \(f_1=8\) and \(f_2=28\) (Table 4) is \(F_0(0.06; 8; 28)=2.31\).

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 \(m_{ij}=m(n,n)\).

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

<table>
<thead>
<tr>
<th>Number of degrees of freedom</th>
<th>Significance level</th>
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<tbody>
<tr>
<td>0.21</td>
<td>0.06</td>
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<tr>
<td>1</td>
<td>12</td>
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<tr>
<td>2</td>
<td>2.814</td>
</tr>
<tr>
<td>3</td>
<td>2.373</td>
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<tr>
<td>4</td>
<td>2.342</td>
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<td>5</td>
<td>2.345</td>
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<tr>
<td>6</td>
<td>1.945</td>
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<tr>
<td>7</td>
<td>1.888</td>
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<tr>
<td>8</td>
<td>1.872</td>
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<tr>
<td>9</td>
<td>1.845</td>
</tr>
<tr>
<td>10</td>
<td>1.823</td>
</tr>
</tbody>
</table>
Table 4

<table>
<thead>
<tr>
<th>Values of the Fisher’s F-criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of degrees of freedom for the denominator</td>
</tr>
<tr>
<td>1</td>
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<tr>
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<td>1</td>
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<td>50</td>
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Table 5

<table>
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<tr>
<th>CFE 2^3 planning matrix takes the form</th>
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<td>K</td>
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<tr>
<td>2</td>
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<td>5</td>
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<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>

Consequently, coefficients of the regression equation are calculated by formula

\[ b_j = \frac{1}{N} \sum_{i=1}^{N} x_i y_i = 0, \]

\[ j = 0,1,...,t. \]

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

\[ s^2 \{b_j\} = s^2 \{y\} / (mN), \]

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 \(N=2^m\) 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 \(b_j = \hat{b}_j + \tilde{b}_j + \sum \tilde{b}_j = \ldots\), 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

\[ U = k_1 x_1 + k_2 x_2 + k_3 x_3 + k_4 x_4, \]

where \(x_1,...,x_4\) are the coordinates of the system TD – asynchronous motor (AM); \(k_1,...,k_4\) 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 \(Q = Q(k_1,...,k_4)\). 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 \(b_0,...,b_4\), and values of the optimized indicator \(Q_o\), calculated using the model.
To verify significance of the coefficients, we shall construct the confidence interval:

\[ \Delta b_i = \pm t(\alpha, f) \sqrt{\frac{s^2(Q)}{N}}. \]

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 \( \alpha=0.06 \) is \( t(0.06; 2)=4.823 \). Variation in the reproducibility, which is determined from the three duplicating experiments, is \( s^2(Q)=0.82\times10^{-3} \). Then

\[ \Delta b_i = \pm 4.823 \sqrt{0.00082/16} = \pm 0.345. \]

Equation coefficient \( b_3 \) is not significant, since condition \( |b_3|>\Delta b_3 \) is not satisfied for it. We obtain \( \hat{Q}=0.4628 -0.1026k_3 +0.0887k_2 +0.0836k_1 \). Employing the Fisher's criterion, we shall check adequacy of the model:

\[ s^2_{ad} = \frac{\sum (Q_i - \hat{Q}_i)^2}{N-L} = 0.0356 \times \frac{14-6}{16} = 0.00445; \]

\[ F_e = \frac{s^2_{ad}}{s^2(Q)} = \frac{0.00445}{0.000822} = 5.43. \]

Thus, the obtained regression equation takes the form

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

The obtained model is adequate because the value of \( F_e \) is lower than the tabular value \( F_e(0.06; 12; 2)=19.56. \) 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 \( \gamma \) 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=2^16, 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 \( \alpha=0.06 \) and at the number of degrees of freedom 30)

\[ f=30t(0.06; 30)-t(0.06; 2)=4.823, \]

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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1. Introduction

Efficient management is the basis of competitive activ-
ity 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 accel-
erated 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 delib-
erately 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 ag-
iculture is not capable of satisfying domestic markets as a
result of ineffective operation of agribusiness.

Development of the agricultural sector in Ukraine sig-
nificantly varies over different regions. The differences are
related to natural resources, climatic conditions, availabil-
ity 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-