Наводяться результати досліджень у рамках удосконалення системи підтримки прийняття рішень при проектуванні суднових енергетичних установок (СЕУ) комбінованих пропульсивних комплексів (КПК). СППР побудована з використанням системного аналізу, оптимізації та технологій моделювання, реалізованих на базі DMI-моделей суден. При удосконаленні СППР було застосовано метод взаємної імплементації характеристичних просторових векторів енергетичних процесів в СЕУ і гідродинамічних в КПК

Ключові слова: суднова енергетична установка, пропульсивний комплекс, моделювання, процес передачі потужності, прийняття рішення

Приводятся результаты исследований в рамках совершенствования системы поддержки принятия решений при проектировании судовых энергетических установок (СЭУ) комбинированных пропульсивных комплексов (КПК). СППР построена с использованием системного анализа, оптимизации и технологий моделирования, реализованных на базе DMI-моделей судов. При совершенствовании СППР был применен метод взаимной имплементации характеристических пространственных векторов энергетических процессов в СЭУ и гидродинамических в КПК

Ключевые слова: судовая энергетическая установка, пропульсивный комплекс, моделирование, процесс передачи мощности, принятия решения

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DECISION SUPPORT SYSTEM'S CONCEPT FOR DESIGN OF COMBINED PROPULSION COMPLEXES

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1. Introduction

In recent decades the growth of capacity, energy-efficiency, increasing prices for fuel and materials, enhanced operational modes, which is associated, first of all, with the development of the offshore fleet, have substantially aggravated the problems of design, construction and operation of the optimal combined propulsion complexes (CPC) and ship power plants (SPP) that provide their power. Today, in the design of ships, along with traditional desire for optimization of dynamic characteristics, more attention is paid to the increase in reliability of the system "propulsion-shaft-hull-engine", taking into account specificity of their work under conditions that are constantly changing. A great complexity of these tasks predetermines the main way to solve them – a physical model experiment and operational and technical economic calculations based on it. The results of such research, as a rule, are published in professional publications, technical materials of the sessions of the International Towing Tank Conference (ITTC) and scientific and technical societies, usually inaccessible when conducting research calculations. The publications that exist in this country mostly do not meet modern requirements as far as applied methods, designations and terminology are concerned [1].

For example, the definition of the tow and established power and towing resistance of the designed ship with the accuracy enough for practice is possible only according to the results of the tests of geometrically similar models under conditions of partial dynamic similarity, which called into existence various methods of processing of obtained results and recalculation for the real conditions.

Mentioned methods have been used for decades and are improved in towing tanks of different countries, which greatly complicated comparison of the obtained intermediate results. A similar pattern is observed in the research of the interaction in the system housing – propulsion, SPP – CPC, etc. Since the beginning of the 20th century systematic tests of series models were conducted to judge the effect of certain parameters that characterize the shape of the underwater part of the hull, the resistance change or parameters, which would increase the SPP efficiency to change the dynamic CPC characteristics. In these cases, a group of models are designed and tested based on the basic models that differ by a regular change of separate elements (adopted in the shipbuilding practice) while other paprameters were unvariable. Before the 70-ies of the last century, the results of serial testing were processed by the accepted in a certain organization methods and were used to construct their own empirical methods of calculation of towing resistance of ships with bypasses of installed capacity of SPP, dynamic characteristics of CPC, etc., built according to the rules in this series or slightly different from them [2]. The accepted method of research by way of "changing the settings one by one" is inaccurate in principle because both the shape of the ship's surface, the dynamic CPC characteristics and SPP effectiveness are the functions of a large number of parameters dependent on each other in various degree, so changing one of them changes others automatically.

As for SPP for a particular type of CPC, then their choice is generally not optimized, neither from the point of view of the efficiency of CPC itself, nor from the point of view of improvement of the operational SPP modes that can be made only by integral methods [3].

With the advent of computer technology, it became possible to process primary results of serial and single model tests using methods of multifactor analysis and to present the results in the form of multi-dimensional surface described in the form of polynomials of the second-third degree of the shape of the hull, hydrodynamic criteria of similarity and SPP efficiency criteria. The work of determining coefficients of polynomials performed over the last decade allowed creating dozens of methods of forecasting of towing and installed capacity of vessels of various types, while the accuracy of these forecasts are substantially higher than traditional methods described, for example, in [4, 5].

With regard to a great complexity of the calculations by these methods, they are implemented mainly in the form of a thoroughly tested computer software that allows users not to challenge the accuracy of the calculations carried out with proper choice of appropriate methodological series considering all the restrictions, provided the initial information was entered correctly.

In recent years, the data of the coefficients of the interaction between propulsions and vessel's hull, fuel and lubricants consumption efficiency, etc., have been processed similarly, which created the basis for creating methods of estimation of influence of structural factors on the propulsive characteristics of ships and efficiency of operational CPC modes.

Software products that were developed in recent years make it possible for an engineer to carry out not only determining the towing and installed capacity, optimal propulsion, but also selecting necessary SPP components. The usage of modern methods increases the culture of designing and gives a researcher an opportunity to learn how to work with professional software products in performing research, which elevates the level of scientific-research work to international standards.

CPC provides continuous abutments on the propulsions (rowing pods) in the movement of the ship to overcome resistance of water and inertia of the hull due to SPP energy providing for maximal efficiency. In the mode, for example, of a dynamic positioning (DP), SPP efficiency takes up not very important, but not the last place. As different types of main engines are used in the CPC for energy generation, however, SPP with diesel as a source of mechanical energy (over 80 %) gained the widest popularity. Modern CPC can be distinguished by the following main SPP types by way of control of progressive movement:

– with heat or electric engines, as well as their combination operating with fixed propeller pitch (FPP) – with these settings the control of the ship's progressive movement is reduced to changing the engine modes;

– with heat or electric engines, as well as their combination operating with controllable propeller pitch (CPP) – with these settings the control of the ship's progressive movement is carried out by the change in operation modes of the main engines and the propeller screw step;

– with heat or electric engines, as well as their combination running on FPP of reverse rotation;

– with heat or electric engines operating on FPP or CPP and electric engines that run on FPP with azimuth degree of freedom;

– with electric engines operating on FPP with azimuth degree of freedom.

The attached SPP CPC graduation is not final, and has a lot of cross-combinations, so to define clearly the type of SPP on the stage of design, to complete the chosen CPC is quite difficult. Therefore the built ships after a certain period of time, sometimes very brief, need recompleting because of the impossibility of working in some operating modes, or due to the decrease in their efficiency.

Control of the ship's progressive movement or keeping the vessel at the desired location is carried out by a combined method using power management systems (PMS) and various regulators and stabilization systems depending on the type of installed components that ensure the start, stop, reverse and frequency change in a propeller screw rotation.

The most suitable for solving various problems of designing SPP CPC are the decision support systems (DSS) that are interactive computer-aided systems (software packages), which are designed to aid and support various kinds of research or project activity when making decisions regarding the solution of design or research problems (structured or unstructured). The application of DSS should provide a comprehensive and unbiased analysis of the subject field, making decisions under conditions of continuous development and SPP CPC complexity [6–8]. The support of DSS computer tools in various approaches should provide the opportunity to design, select and directly compare alternative solutions.

There are many technologies, criteria and, as a result, the methods used in DSS for the design of SPP CPC. And the choice of one or another way with the final goal of obtaining the rankings of alternative solutions should rely on the initial data, knowledge and the results obtained in the process of decision-making.

On the other hand, the lack of qualified personnel in connection with their departing research institutions, increasing requirements to the intensity and quality of production, competition in the sector of design and construction of SPP CPC are additional factors that determine the relevance of the DSS. Methods and simulation tppls used in this area do not fully correspond to modern problems. At the same time, research in the field of artificial intelligence and expert systems, in particular, have shown the efficiency of application of intelligent DSS in such cases, based on expert knowledge. However, in the area of providing energy efficiency of designed SPP CPC, especially in the modes of dynamic positioning, development and industrial application of DSS remains unsolved.

Thus we can state that the development of DSS in the design and research of SPP CPC, with the introduction of its components in energy processes in order to increase the effectiveness of the decisions is a relevant issue, especially when choosing one or another CPC structure, setting up various regulators, contributing to the improvement of operational modes of a ship.

2. Analysis of scientific literature and the problem statement

While solving the problems of a system approach in making decisions in research work at SPP CPC designing, a number of uncertainties [9] occurs, such as:

– the problem of the choice of adequate targets and goals in the study of energy processes in the power transfer in SPP CPC with many interdependent criteria;

– the uncertainty of the impact of unidentified state of the environment that are uncontrollable while affecting operational modes;

– the absence or lack of sufficient knowledge about the nature of the origin of the disturbing factors and their influence on energy processes;

– the ambiguity of expectations of the SPP CPC development with a prospect of upgrade;

– the vagueness of directions and strategies of the development of the SPP CPC components, or the so-called diversity of approaches from different manufacturers at the evaluation of parameters and SPP CPC characteristics;

– fuzzy and diverse information space in coverage and interpretation of research results of processes and objects, as well as the absence or unavailability of authoritative evidence on the reliability of existing information.

In addition to the mentioned above, worth noting are:

– uncertainty of structures and parameters of the models of studied SPP CPC;

– difficulties of system analysis and quality of evaluation of the models parameters;

– the absence or unavailability of statistics of the observed systems, which are a part of amount of the data with available omissions, pulse emissions, disturbing influences and errors (noise) in measurement;

– ambiguity of methodology research from various, sometimes unrecognized data processing techniques or solving problems;

– the impossibility of organizing all the possible options of SPP CPC set, which derives from all the types of uncertainties and is essentially caused by them.

In [10] the design and implementation of SPP CPC in the DP mode with the help of simulation of a hardware loop in the controller of regulation speed of a rowing engine was implemented, but the problem of dynamic load of mathematical models and practical realization of the work remained.

The problem of topology and design of power transformers is considered by the authors in [11], but evaluating the effectiveness, design and potential operation characteristics in SPP CPC use remained unsolved. Also unanswered is the question of comparison with other types of power transformers to establish whether a specific type of transformer has potential by its topology to improve the operational SPP and CPC characteristics.

Today there is not a unified strategy for DSS construction in the design and study of SPP CPC but the main principles have already been formed. Thus, DSS that is developed should be: at the level of the user – cooperative, which allows a designer or a researcher (a person who makes a decision – PMD) to modify, improve and complete the solutions offered by the system, sending these changes in the opposite direction for testing; at the technical level – a local system, which may be installed on one computer, due to the necessity of PMD mobility; at the conceptual level – model-driven (DSS) and provide access to the study of mathematical models (statistical, DMI-models, optimizing, imitation); depending on the types of data that DSS will work with is strategic, based on the analysis of large volumes of various information from alternative sources [12].

In [13] the issue of modern DSS SPP CPC were developed in the direction of definition of requirements for the general structure of the system of design and PMD training but simultaneous modelling of SPP and CPC structures and their implementation led the authors to difficulties with DSS practical usage.

In particular, in [14] this issue was partially solved in terms of the application of new generation of DSS to provide a wider range of possible solutions and reduce costs, but the choice of performance criteria and their approach to the dynamics of physical models did not produce desired results.

And finally in [15] the authors tackled the issue of optimization of dynamic characteristics and initiated the design of control strategy of SPP CPC, but the study of models of nonlinear controllers and simulation models SPP CPC in Matlab/Simulink was performed without adapting the software to other DSS. The problem of matching and dispersal of parameters that are explored in the case of deviation of SPP capacity was also not considered.

The most important aim of the created DSS is to improve the most rational options of SPP CPC set, taking into account the influence of various factors with the possibility of deep consideration of the data, knowingly converted for convenient use in the decision-making process and to work out the rules for making decisions, which on the basis of the data, accordingly consolidated, will enable a PMD to justify making a decision, using improving factors when upgrading SPP CPC and increase their efficiency. DSS should be based on multi-dimensional principles of representation and analysis of the data [16].

Goals and purpose of DSS can be defined as follows:

– creating the conditions for understanding the problem to be solved that is problem structuring, generating the main and auxiliary tasks, identifying existing advantages and disadvantages, formation of criteria;

– asisstance in solving problems, that is a possibility of generating and selecting different types of models and methods, collection, processing, and preparation of data, calculation, design, delivery and adjustment of the results;

– assistance in conducting regressive analyses, etc., an explanation of the selected ways of decision;

– ability to analyze similar and alternative solutions and availability of results [17].

A cognitive process is mainly used for the functional structuring of DSS at the design of the SPP CPC (Table 1) [18].

Logical steps in creating the DSS will be detailing of the stages in the design of SPP CPC, functional structuring of its architecture and the substantiation of the process of implementation. Using the deepest data analysis, complex of engineering knowledge, etc., linked to the relevant tasks of the DSS designed computing procedures, then connect functions and procedures, and, eventually, to realize all the stages of the programming of all the functional system modules, including the design and programming of interface between PMD and DSS.

Therefore, making the conclusion, we can state that from the point of view of modern requirements, the present situation requires creation of DSS at the design and study of SPP CPC, which will give an opportunity: to manage data;

to have sufficinet information about the decision-making that hides original assumptions, quantitative and qualitative evaluation; to control calculation and modelling, including flexibility and the capacity to generate DMI-models of SPP and CPC; to have an opportunity to improve the made decision, as well as SPP CPC efficiency, typification and design of the software elements, testing simulation models, comparing the results of running tests and laboratory studies with theoretical works.

Table 1

Process of cognitive design of DSS

Scientific tools	Scientific problems (stages)	Scientific results, methods of implementation
Processing of the results of the analysis of periodicals	Substantiation of the relevance of DSS design at SPP CPC projection	Recommendations for further DSS improvement
Protocol of initial data collection and the problem decomposition	Statement and decomposition of problems for DSS	Table of necessary requirements to DSS
The list of existing and possible limitations during making decisions in the design process	Definition and the list of limitations that can arise in the decision-making process	The list of specific problems for a certain task
Necessary DSS functions at SPP CPC design	Definition of functional capacities of DSS	The list of available DSS functions
The list of methods and existing rules for the decision selection	The design of methodology and ways of making decisions	Functional structuring
Systems of automatical projection, algorithmic languages, visualization programs	Typification of dialogue windows, DSS control principles and usage of necessary software medium	Block-schemes of algorithm, verbal algorithms of work, engineering methods
Simulation software products	Developing software medium and its approbation, protocol of approbation	Algorithms, block-schemes, graph-schemes, programs, identification m-files

3. The purpose and objectives of the study

The aim of the studies is the synthesis of a decision-making support system in the design of ship power plants (SPP) combined propulsive complexes (CPC), required for the improvement of occurring energy processes in SPP CPC.

To achieve this aim the following tasks were set:

– statement and decomposition of the problems regarding DSS in the design and study of energy processes in SPP CPC with determining operational and combinatorial constraints and substantiation of the functionality of DSS in the design and study of SPP CPC;

– ensuring functional compliance of modeling steps of the processes of power transfer, composition of operating modes and criteria for the evaluation of SPP CPC effectiveness, information correction, automation of analysis with the ability of logical conclusions, support of presentation of the results and improvement of the quality of the made decision;

– development of methods and ways of improvement of the made decision from the point of view of SPP CPC efficiency, development of the elements of the software medium and their testing in the simulation modeling in real conditions during running tests and laboratory studies.

4. 1. The setting and decomposition of the problems considering boundary conditions and criteria

When performing decomposition of the main goal, situational purpose was set, that is the study and identification of mathematical models of operational modes of SPP CPC in existing software complexes, other DSS in order to detect drawbacks and existing assumptions and criteria, on the basis of which the present dynamics of problem solving were formed by way of consistent interactive analysis of situational data, when the formed problem or its absence is considered as a result of solving or complicating (refinement) of the previous one.

Achieving situational purposes, the criteria of selection decisions were formed and combined based on a set of both SPP CPC and operating modes in which they operate. In some cases herewith the problems of knowledge occurred, in which the clarity of strategy and selection rules of alternative criterion were lost. Based on the fact that most of the criteria had numeric character, the necessity arose to perform complex calculations in the process of merging various, sometimes, at first glance, incompatible criteria that led to dividing them into determining and defining.

For example, integral criteria of effectiveness allow making a decision at variation of any significant parameters of SPP CPC that would provide the increase of energy efficiency, and therefore if the adequacy of mathematical models is provided, the criteria can be considered objective and applicable for assessing the efficiency of the power transmission in this SPP CPC with any types of engines on the shafts lines. In the stationary movement of the ship with CPC, the resistance to the body that moves, is proportional to the traction, but in general case the resistance to movement R and the traction T should not necessarily be equal and opposite, and the ship in this case may accelerate and react to other external forces. In this case, the coefficients, that take into account the reduction of the traction, can be identified using the replacement of the resistance by the relevant efforts for all three planes of the movement (surge, sway, yaw) [19, 20]:

$$C_{F_{Lh}} = \frac{F_L(V,n) - T_{ux}(V,n) - F_L(V,0)}{T_u(V,n)}, \tag{1}$$

$$C_{F_{Th}} = \frac{F_T(V,n) - T_{uy}(V,n) - F_T(V,0)}{T_u(V,n)}, \tag{2}$$

$$C_{N_h} = \frac{N(V,n) - T_{uy}(V,n)X_p - T_{ux}(V,n)Y_p - N(V,0)}{T_{uy}(V,n)X_p - T_{ux}(V,n)Y_p}, \tag{3}$$

where $F_L(V,n)$, $F_T(V,n)$ and $N(V,n)$ are the general forces (H), acting on the vessel in the absence of other external disturbances at the flow velocity v (m/s) and the relevant number of FPP turns n (r/min); $F_L(V,0)$, $F_T(V,0)$ and $N(V,0)$ are the relevant forces (H) in the case of fixed propeller screw (for example, flow); $T_{uy}(V,n)$ and $T_{ux}(V,n)$ are the tractions (H) by the relevant axis relative to the plane of the movement.

Based on the formulas for calculating the capacity for any engine, directly transmitted to the propeller screw, we find the expression for the calculation of the coefficients of efficiency on the shaft line under the influence of forces that act in a certain plane, where these forces have the advantage. For example, for the induction motor [21]:

$$P_{AD} = \eta_{TRM} \cdot 2\pi \cdot Q_{AD} \cdot n, \tag{4}$$

where η_{TRM} is the transmission efficiency, Q_{AD} is the torque on the shaft AD, Nm, and considering the expressions (1)–(4), for the plane surge, we receive:

$$H_{pr\_surge} = \eta_{TRM} \frac{\int_0^L \left(\left|\left(Q_{AD\_F_L}(l) - Q_{AD\_ux}(l)\right)n\right| - Q_{AD\_F_L}\right)dl}{\int_0^L \left(\left|\left(Q_{AD\_F_L}(l) - Q_{AD\_ux}(l)\right)n\right| - Q_{AD\_F_L}\right)dl + \sum_{j=1}^{n}\int_0^L \Delta Q_j(l)dl}. \tag{5}$$

Similarly we receive expressions for calculating AD efficiency for the other two planes:

$$H_{pr\_sway} = \eta_{TRM} \frac{\int_0^T \left(\left|\left(Q_{AD\_F_T}(t) - Q_{AD\_uy}(t)\right)n\right| - Q_{AD\_F_T}\right)dt}{\int_0^T \left(\left|\left(Q_{AD\_F_T}(t) - Q_{AD\_uy}(t)\right)n\right| - Q_{AD\_F_T}\right)dt + \sum_{j=1}^{n}\int_0^T \Delta Q_j(t)dt}, \tag{6}$$

$$H_{pr\_yaw} = \eta_{TRM} \left(\frac{\oint\!\!\oint_{XY} \left|\left(Q_{AD\_N}(t) - Q_{AD\_uy}(t)\right) - Q_{AD\_ux}(t)n\right|}{\oint\!\!\oint_{XY} \left|\left(Q_{AD\_N}(t) - Q_{AD\_uy}(t)\right) - Q_{AD\_ux}(t)n\right| + \sum_{X=Y}^{X} \oint\!\!\oint_{XY} \Delta Q_{XY}(t)dt} - \right.$$
$$- \frac{Q_{AD\_T}dt}{\oint\!\!\oint_{XY} \left|\left(Q_{AD\_N}(t) - Q_{AD\_uy}(t)\right) - Q_{AD\_ux}(t)n\right| + \sum_{X=Y}^{X} \oint\!\!\oint_{XY} \Delta Q_{XY}(t)dt} -$$
$$\left. - \frac{Q_{AD\_N}dt}{\oint\!\!\oint_{XY} \left|\left(Q_{AD\_N}(t) - Q_{AD\_uy}(t)\right) - Q_{AD\_ux}(t)n\right| + \sum_{X=Y}^{X} \oint\!\!\oint_{XY} \Delta Q_{XY}(t)dt} \right). \tag{7}$$

On the other hand, for promising concepts of SPP CPC with hybrid ship installations with contra-rotating pods (CRP), working in the mode DP where gravitational forces dominate and Froude law of similarity applies, to receive which the equality of numbers for the model and nature is needed, i. e. $F_{rM}=F_{rN}$, criteria of similarity are necessary to express through the values characteristic for a given mode.

When water flows around the ship hull in a characteristic linear size, they choose the length of the ship between perpendiculars on the waterline and forward in the direction of the flow, and as the characteristic speed – the speed of the flow attack.

The Froude similarity criteria for our case is obtained from the general criterion of hydrodynamic similarities of Newton, substituting the force of gravity to this equation, G=mg:

$$\frac{v_S^2}{g_S \cdot l_S} = \frac{v_M^2}{g_M \cdot l_M}, \tag{8}$$

where v is the running flow speed, m/sec; g is the force of gravity, m/sec^2; l is the length, m, accordingly (S) of the ship and (M) of the model.

It is necessary to receive main parameters of all emerging flows from the equation (8) taking into account the extent of the similarities. We calculate in which dependencies speed, thrusts and torques for the model and the ship are in the case of modeling by the Froude's law.

Records of cavitation occurrence is carried out by maintaining the criteria of similarity F_r, R_e and equality of numbers E_u for the model and the ship.

In fact, the resistance of a ship consists of both the resistance to friction and wave resistance, caused by waves, that forms on the free surface of the water under the force of gravity. However, later PMD will meet the next complication: if the size of the model is 100 times less than the size of the actual ship, then by the equation, to keep the Froude's number F_r unchanged, one needs to take the speed of v by 10 times less than the speed of the actual vessel, and in order to keep the Reynolds number R_e also unchanged, the coefficient of density ρ must be taken by 1000 times lower than the density water coefficient. But it is impossible to do in practice, that is why the test should be conducted in the same medium, to use the same water and the friction resistance should be determined by the special research formulas, and residual resistance, i. e. wave resistance, has to be recalculated according to the law of similarity for ideal incompressible liquid that is under the influence of gravity force.

Resistance to the movement of the vessel depends on the shape of the hull. Studying the influence of the hull's shape, it is necessary to expand the class of motions and examine the movement of the family of hulls, formed by some law depending on geometrical parameters, the change of which characterizes the studied geometric features of the contours.

It is very important in practice to highlight the following options from infinite variety of parameters that characterize geometric properties of the shape of hulls, such options that are very important for the residual resistance.

Experimental research in the field of hydrodynamic simulations show [22] that the main parameters for all sorts of geometrically dissimilar contours of the hulls of usual types of ships that determine the coefficient of resistance is a Froude's number and a coefficient of sharpness. Instead of a Froude's number by length, it is possible to take Froude's number by the volume water tonnage Δ:

$$F_{r\Delta} = \frac{v}{\sqrt{g\sqrt[3]{\Delta}}} = F_r\sqrt{\lambda}, \tag{9}$$

where λ is the coefficient of longitudinal hull sharpness (Fig. 1) [23].

If for the real conditions and the conditions of the test of a model the acceleration of gravity $g_S \neq g_M$, then from (8) we receive:

$$\frac{v_S}{v_M} = \sqrt{\frac{l_S \cdot \rho_1}{l_M \cdot \rho_2}} = \sqrt{\lambda_{SM}}, \tag{10}$$

where ρ_1, ρ_2 are the densities of the media, kg/m^3, that is the speed of a model water flow should be decreased by $\sqrt{\lambda_{SM}}$ under condition of compliance with Archimedes criterion for a real and a simulation medium.

So, the abutments of the model and the ship pods should be in dependence:

$$\frac{T_S}{T_M} = \frac{n_S \cdot v_S}{n_M \cdot v_M} = \lambda_{SM}^2 \sqrt{\lambda_{SM}} = \lambda_{SM}^{2,5}, \qquad (11)$$

where n_S, n_M are the frequencies of pod rotation, r/min; that is, if an abutment of the ship pod T_S, then at the smaller by l_{SM} times model, the abutment of the pod should be lower by $\lambda_{SM}^{2,5}$ times under condition of compliance with geometrical criteria of similarity.

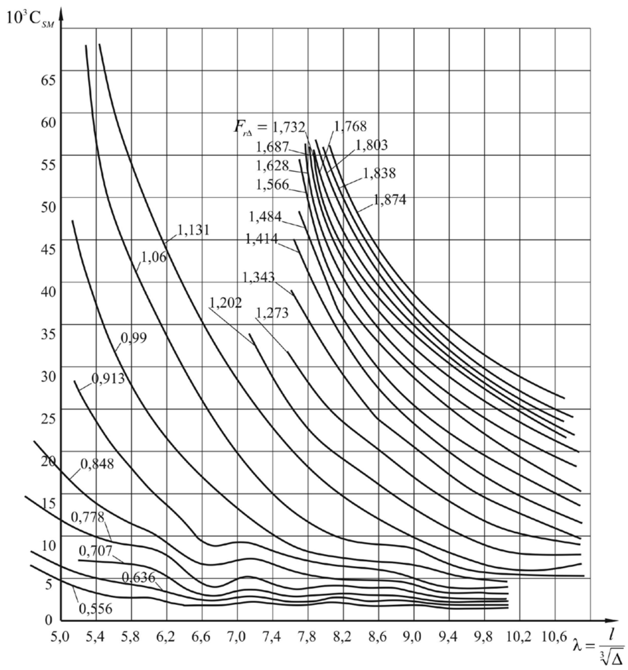

Fig. 1. Experimental dependencies of the ratio of resistance on a ton of water tonnage in the function of coefficient of longitudinal hull sharpness and Froude's number

The ratio of torques on the pods' shafts, and therefore the capacity consumed by the drive engines, considering the correlation (8)–(11), i. e.

$$\frac{Q_S}{Q_M} = \frac{D_S \cdot v_S}{D_M \cdot v_M} = \lambda_{SM}^{2,5} \sqrt{\lambda_{SM}} = \lambda_{SM}^{3}, \qquad (12)$$

where D_S, D_M are the diameters of pods, m.

Similarly, through the linear scale one can deduce the values of the scale factors for other parameters.

4. 2. Support of functional compliance of the processes with the design problems

Technologies of the design of SPP CPC require the following functions to support decision-making by PMD:

1. Modeling of the processes of power tranfer. With the help of existing models of real processes, or in the process of creating the new ones, it is necessary to have a possibility to apply, based on the regressive approach of the subsystem of forecasting their further process and subsystem of synthesis of optimal and adaptive solutions that are based on current data, or observations [24, 25].

2. Composition of operating modes and criteria for evaluation of effectiveness of SPP CPC. With the help of mathematical methods of finding tools or rules to combine automatically those properties that characterize different operating modes of SPP CPC for removal of cognitive limitations of PMD.

3. Information correction. Reading, saving and processing of information, data, results using integrated computer technologies, due to which the capacities of PMD in decision-making and data processing expand significantly.

4. Analysis automation with the ability of logical conclusions using artificial intelligence methods and numerical methods that will allow improving the quality of the results and reduce the time for solving similar problems in future.

5. Support for the presentation of the results with the implementation of the functions of access to databases and knowledge bases of other DSS, using the tools of computer graphics and language processing as well.

6. Improvement of the quality of decision making in order to eliminate errors in systematics, stemming from the quantitative analysis and heuristic calculation, by the introduction of statistical and other methods of correction results with functional design and selection of specific procedures of calculation and analysis for the implementation of each function of the DSS within the existing group of experts who design it, to eliminate external and cognitive restrictions that affect making a decision.

For example, it is possible to display the reservation index of the ship technical means and equipment by a function of coefficients of reservation, i.e. the ratio of the number of installed objects onboard to the required number of these objects, according to the rules of the Register. Each element of the SPP CPC requires the analysis of evaluation from PMD considering requirements depending on the type of the ship, operating modes and the area of navigation.

The rules of registers concerning the number of main engines are not set. The number of main engines is defined according to the technical specifications for a ship design and, consequently, by a ship owner, so it is advisable to exclude the main engines from a number of factors of the reservation indicator.

The number of main sources of electric power is chosen based on the results of the calculation of the power of the ship's electric plant. In addition, each self–propelled vessel must be provided with not less than two main sources of energy (two generators driven by own source of energy; a generator driven by own source of energy and a shaft generator; a generator driven by own source of energy and a storage battery). But the power from the main sources of electricity must ensure that in the case of failure of a single source, the remaining ones provide the electricity supply to critical devices in the running, maneuvering and emergency modes. That is, the operation of a ship in the mode, for example, of staying put, based on these terms, is not specified. In reality, there are four or more major sources of electrical energy on the ships of the class DP. Besides, the rules of the registers imply the need for the installation of emergency sources of electric energy beyond the engine-boiler room (EBR).

The performed analyses [26] considering various types of vessels justify PMD decision and the requirements of the registers and European requirements for the number of sources of electrical energy are different, that is why the sources of electrical energy is expedient to include into a number of factors that affect the indicator of the reservation.

According to the registers rules, the vessels of DP class must be provided with one main fire-extinguishing pump and the pump as a part of the ballast system, except for the vessels longer than 100 m, where there must be two main fire pumps and two pumps that are able to work with the ballast system. Besides, oil and drilling vessels longer than 100 m must be provided with at least one emergency fire pump.

And in this case the performed tests [27] considering vessels of different types allow PMD to make a decision that the requirements of the registers and European requirements for the number of fire and ballast pumps are not identical, so the fire and ballast pumps are also included in the number of factors that affect the indicator of the reservation.

Finally, regarding the drainage pumps, each vessel must be provided with not less than two drainage pumps, one of the pumps must be ballast, included into the drainage and ballast systems and working in a DP mode. The second pump may be ballast, sanitary, of general usage, with water or steam ejector and not included in the process of calculating SPP power. In other words, it may be stated that according to the analysis [28], the requirements of the registers and European prescriptions concerning the number of drainage pumps for certain types of ships, operatingg in a DP mode, do not exist at present at all, so the drainage pumps are also included in the number of factors that affect the indicator of the reservation.

From the point of view of supporting the compliance functionality, there is no sense to apply quality criteria, which might be imposed on PMD, because in our conditions they are not relevant, in particular as a result of poor competitiveness of domestic scientific decisions in the domestic market.

The next step is likely to be highlighting primary (initial) processes in the design and study of SPP CPC, that is the description of physical processes with which the PMD will be required to interact.

4. 3. Technology of DSS SPP CPC implementation including intellectual, behavioral anf cognitive restrictions of PMD

SPP CPC design from the point of view of considering all functional restrictions within a single operating mode presents a cognitive (in synergy with the engineering) research process of making a decision that includes gradual improvement of the data that come from the study of a particular operational mode of a vessel and SPP operation as well, together with modern technological operational DSS base. One of the steps was considered in previous subchapters. Modern requirements in the support of decision making were found in advance at the stage of substantiation of requirements to functional compliance with the processes of the design problems.

Requirements to support decision making in the design of SPP CPC determine functional restrictions which PMD who uses DSS should bypass. The next stage specifies specific needs in support of the decision that integrate with developed and implemented methods within the DSS based on the characteristics of the operational mode without the use of supporting scientific research tools, i.e. only on the basis of available data and the results of other works within existing DSS. In this way a conversion of a specific request in support of making a decision into a functional project of SPP CPC is achieved. The main technological tool that is needed at this stage is more or less precise substantiation and application of technological DSS base, which in its turn, is based on functional qualities and defined criteria explored above. A mathematical apparatus used in the design and implementation of SPP CPC within DSS is shown in Fig. 2 [29, 30].

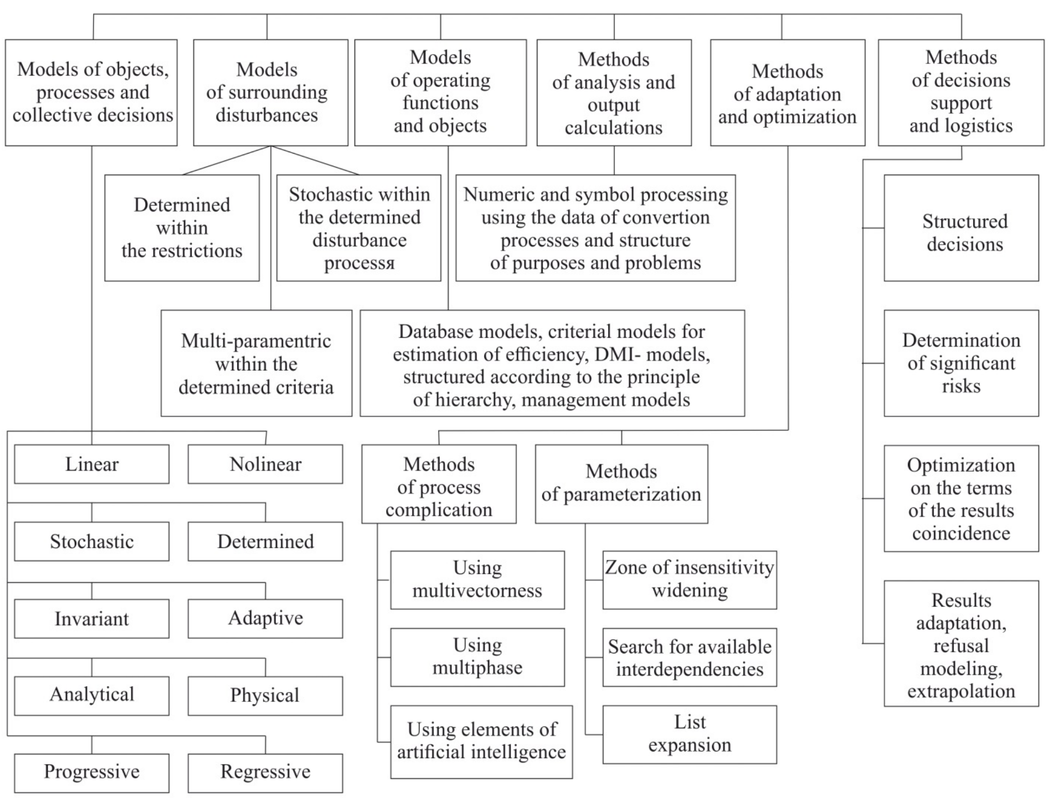

Fig. 2. Classification of mathematical apparatus of DSS in the design and research of SPP CPC

According to the given classification (Fig. 2), simulation of real processes, control systems or SPP CPC control within DSS that is created should be carried out with an ability of choice of alternative decisions, a diverse toolkit for information retrieval, methods of automated analysis and applications for the presentation of results, implementation and improvement of the quality of made decisions. Each model should be built taking into account modern techniques with the ability to implement the support functions. The use of one or another method within each subsystem of DSS should be based on defined and proven criteria and dimensions that determine the level of their adequacy in a particular configuration of SPP CPC.

It follows that the classification presented in Fig. 2 not only directs the PMD in the appropriate direction, but also specifies the issues of making a decision that is considered when choosing a method of SPP CPC study for its further implementation within DSS. Certainly, the classification presented in Fig. 2 does not provide comprehensive support for the design of SPP CPC but determines the list of available modern technologies for its implementation and methodology of research within the defined methods and specifies tools for comparative analysis. For the implementation of deep comprehensive analysis of the made decision regarding the projected SPP CPC it should have a set of recognized rules, based on reliable data from decision making in this area, which were collected by decomposition of specific operational problems which would have enabled to implement the developed SPP CPC at the lowest risks for operational inefficiency.

5. Computer simulation of the processes in SPP CPC as a DSS component

Fig. 3 presents a computer model for setting thrusters configuration on the example of CPC of the ship of the type Supply Vessel.

According to the method described in [31, 32], a computer model was created of identification of the parameters (Fig. 3) of the ship, the type Supply Vessel, the m-file text of which is given in the item 5 of the research results.

For the step ratio $p_{Di}=H_P/D_i$ the values of thrusts and torques are determined by the force vector τ_T, that is described by the equation

$$\tau_T = T_{matrix} K_{Tmatrix} u_T, \tag{13}$$

where T_{matrix} is the matrix of thrusters configuration (16)–(19); $K_{Tmatrix}$ is the matrix of coefficients of pods thrusts (15); u_T is the vector of removable thrusters thrusts applied to the ship (14).

The thrusts applied to the ship in a dynamic positioning mode, due to thrusters work, are determined by the force (thrusts) vector:

$$u_T = \Big[\left|p_{D1} - p_{D10}\right|\left(p_{D1} - p_{D10}\right), \left|p_{D2} - p_{D20}\right|\left(p_{D2} - p_{D20}\right), \ldots,$$
$$\left|p_{Dk_{TR}} - p_{Dk_{TR}0}\right|\left(p_{Dk_{TR}} - p_{Dk_{TR}0}\right)\Big]^{T_{matrix}}, \tag{14}$$

where p_{Di0} (i_0=1...k_{TR}) is the step ratio of separate thrusters pod, maximal quanity of which is determined by the number k_{TR}.

Coefficients of pods thrusts are determined by the diagonal matrix:

$$K_{Tmatrix} = \begin{pmatrix} K_{T1}(n_1) & 0 & \ldots & 0 \\ 0 & K_{T2}(n_2) & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & K_{Tr}(n_r) \end{pmatrix}, \tag{15}$$

where n_i (i=1...r) is the frequency of i thrusters pod rotation, r/min.

Forces of thrusters thrusts determined by the vector (13), are divided into the lengthwise, crosscut and angle (yaw) components by the matrix of thrusters configuration.

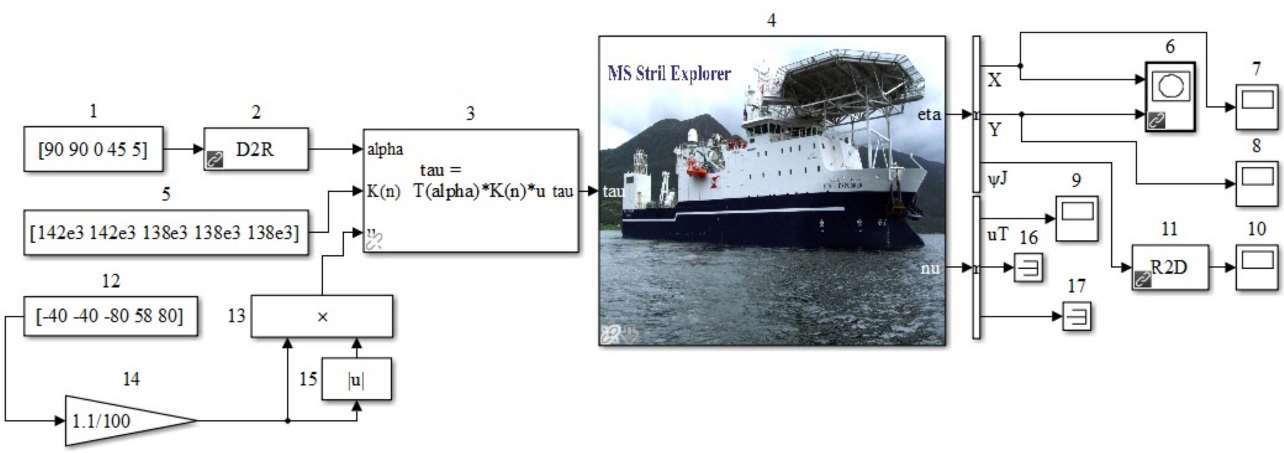

Fig. 3. Computer simulation in MatLab Simulink of the configuration of thrusters for the ship of the type Supply Vessel: 1 is setting the angle of the location of azimuth devices relative to diametral plane of the vessel, α_A, degree; 2 is the block of conversion degrees to radians; 3 is the CPC model; 4 is the model of identification of the ship parameters; 5 is setting the coefficient of the pod's abutment, K_T; 6 is the plotter of XY-coordinates; 7–10 are the oscilloscope fixing: XY are the coordinates of the ship, m; value of weighted force that applied to the ship u_T, H×10^6; an angle of the ship yaw ψ_J, grade, accordingly; 11 is the block of conversion of radians to degrees; 12 is setting the step ratio of pods H_P, −100 % ÷ +100 %; 13 is the function of multiplying; 14 is the block of calculation of step ratio p_D=H_P/D, where D is the pod diameter, m; 15 is the block of calculation of absolute value; 16, 17 are the devices of absorbtion of outgoing signals of the ship which are not tracked

For example, on the ship of the type Supply Vessel four azimuth thrusters are installed (two main and two auxiliary, located between the diametral plane and the fore part to stand out from the hull), which can be rotated at any angle α_A relative to a diametral plane of the vessel and one fore tunnel thrusters. Based on this, we have the following configuration of the thrusts applied to the ship: $u_{T1,2}$ are the thrusts of main azimuth thrusters; $u_{T3,4}$ are the thrusts of auxiliary thrusters; u_{T5} is the thrust of the bow thrusters. Then the matrix of thrusters configuration will have the following look:

$$T_{matrix(0)} = \begin{pmatrix} \cos\alpha_{A1} & \cos\alpha_{A2} & \cos\alpha_{A3} & \cos\alpha_{A4} & 0 \\ \sin\alpha_{A1} & \sin\alpha_{A2} & \sin\alpha_{A3} & \sin\alpha_{A4} & 1 \\ l_{T1}\sin\alpha_{A1} & l_{T2}\sin\alpha_{A2} & l_{T3}\sin\alpha_{A3} & l_{T4}\sin\alpha_{A4} & l_{T5} \end{pmatrix}, \quad (16)$$

where l_{Ti} (i=1...5) is the strength or distance from the place of thrust application of this thrusters to the projection of the force vector τ_T to the plane of the ship's movement.

Moreover, it should be taken into account that positive movement of the ship in the x-direction is a forward movement, in the y-direction is the movement to the right, in z-direction (yaw) – movement back, i. e. contrary to a minute arrow.

For this vessel, as a test of the effectiveness of the existing installation of SPP CPC within the developed DSS, in addition, besides the main, three possible thrusters configurations were tested which are determined by the respective matrices $T_{matrix(1)}$ (17); $T_{matrix(2)}$ (18); $T_{matrix(3)}$ (19).

Configuration (1): two main classical FPP of the left and right sides in the stern of the ship; one azimuth thrusters that stands out of the hull in the fore of the vessel, which can be rotated at any angle α_A relative to diametral plane of the vessel, and one fore tunnel thrusters ($u_{T1,2}$ – thrusts of the main classical FPP; u_{T3} – thrust of auxiliary azimuth thrusters, u_{T4} – thrust of the bow thrusters:

$$T_{matrix(1)} = \begin{pmatrix} 1 & 1 & \cos\alpha_{A3} & 0 \\ 0 & 0 & \sin\alpha_{A3} & 1 \\ l_{T1} & -l_{T2} & l_{T3}\sin\alpha_{A3} & l_{T4} \end{pmatrix}. \quad (17)$$

Configuration (2): two main classical FPP of the left and right sides in the stern of the ship; two stern tunnel thrusters; one azimuth thrusters that stands out of the hull in the fore part of the vessel, which can be rotated at any angle α_A relative to diametral plane of the vessel; one fore tunnel thrusters ($u_{T1,2}$ – thrusts of the main classical FPP; $u_{T3,4}$ – thrusts of the stern tunnel thrusters; u_{T5} – thrust of the auxiliary azimuth thrusters, u_{T6} – thrust of the bow thrusters):

$$T_{matrix(2)} = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & \cos\alpha_{A6} \\ 0 & 0 & 1 & 1 & 1 & \sin\alpha_{A6} \\ l_{T1} & -l_{T2} & -l_{T3} & -l_{T4} & l_{T5} & l_{T6}\sin\alpha_{A6} \end{pmatrix}. \quad (18)$$

Configuration (3): three azimuth thrusters (two main left and right sides and one auxiliary, located between the diametral plane and the fore part that stands out of the hull) which can be rotated at any angle α_A relative to to diametral plane; one stern tunnel thrusters; one bow tunnel thruster ($u_{T1,2}$ – thrusts of the main azimuth thrusters; u_{T3} – thruster of the stern thrusters; u_{T4} – thrust of auxiliary azimuth thruster, u_{T5} – thruster of the bow tunnel thruster):

$$T_{matrix(3)} = \begin{pmatrix} \cos\alpha_{A1} & \cos\alpha_{A2} & 0 & \cos\alpha_{A4} & 0 \\ \sin\alpha_{A1} & \sin\alpha_{A2} & 1 & \sin\alpha_{A4} & 1 \\ l_{T1}\sin\alpha_{A1} & l_{T2}\sin\alpha_{A2} & -l_{T3} & l_{T4}\sin\alpha_{A4} & l_{T5} \end{pmatrix}. \quad (19)$$

Simulation was performed in the computer laboratory MatLab Simulink.

Changing the parameters of matrices of thrusters configurations, mutual location of azimuth devices and their position relative to the diametral plane of the vessel, as well as the step ratio of the pods, we obtained the diagrams of XY-coordinates and the angle of the ship yaw.

6. Results of the study of a ship behavior at different parameters of propulsion complex

We developed m-files of indefication parameters for different types of vessels for their further implementation into a spatial model of SPP with the aim of obtaining optimal XY-movement from the point of view of minimization.

M-file of indefication parameters of the ship, type Supply Vessel, which is in a dynamic positioning mode, is given below:

```
function xdot = supply_vessel(x,Ttau)
% function xdot = supply_vessel(x,Ttau) returns speed derivative by time xdot = E*Ttau + F*x state vector:
x = [u v r x y psi]' for Supply Vessel of the length L = 76 m.
% Model of Zero speed (DP)
% u = speed of longitudinal movement, m/sec
% v = speed of lateral movement, m/sec
% r = yaw speed, rad/sec
% x = position in x–direction, m
% y = position in y–direction, m
% psi = yaw angle, rad
% Ttau = [X, Y, N]' thrust/point vector
% Parameters of the ship
Ls = 76.4; % length of the ship, m
gs = 9.8; % acceleration of the force of gravity, m/c2
tonn = 3657e3; % weight, kg
Tm = diag([1 1 1 1 Ls]);
Tminv = diag([1 1 1 1 1/Ls]);
% Matrices of models
Kmod = [1.1323 0 0 0 0
0 0 0 1.9101 –0.0751
0 0 0 –0.0567 0.1312];
Cmod = [0.0401 0 0 0 0
0 0 0 0.1211 –0.0131
0 0 0 –0.0038 0.0312];
% Checking the initial and original sizes
if (length(x) ~= 6),error('x–vector must have a dimension 6 !');end
if (length(Ttau) ~= 3),error('u–vector must have a dimension 3 !');end
K = (tonn*Tminv^2)*(Tm*Kmod*Tminv);
C = (tonn*Tminv^2)*(sqrt(gs/Ls)*Tm*Cmod*Tminv);
F = [ zeros(3,3) eye(3)
zeros(3,3) –inv(K)*C ];
E = [zeros(3,3); inv(K) ];
% Definition of derivative status
xdot = E*Ttau + F*x;
```

Fig. 4, 5, accordingly, present the diagrams of the changes of XY-coordinates and an angle of yaw ψJ in the function of time during 200 sec from the vessel of the type Supply Vessel at different configurations of thrusters, mutual position of the axes of the main and auxiliary pods relative to diametral plane; values and coefficients of step ratios and thrusts coefficients.

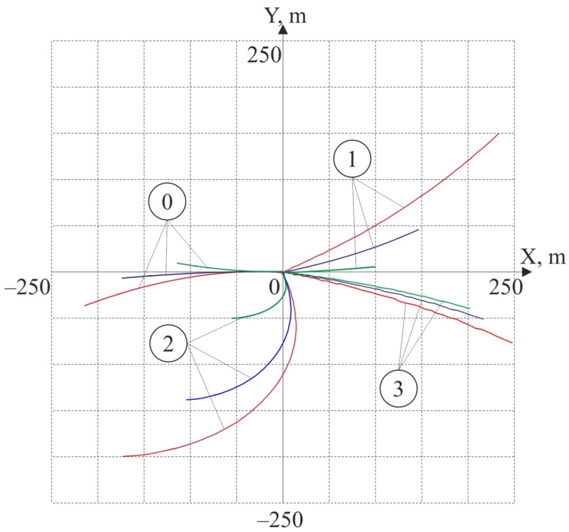

Fig. 4. Changing coordinates of the vessel, type Supply Vessel, length 76 m, at different thrusters configuration: 0—3 — numbers of appropriate configurations (16)—(19): ——— — mutial perpendicular axis location of the main and auxiliary pods with unchanged values of step ratios and thrusts coefficients; ——— — mutial perpendicular axis location of the main and auxiliary pods with regulated values of step ratios and thrusts coefficients; ——— — optimal location of the axes of the main and auxiliary pods with values of step ratios and thrusts coefficients that meet the criterion of minimum change in the XY-coordinates of the ship

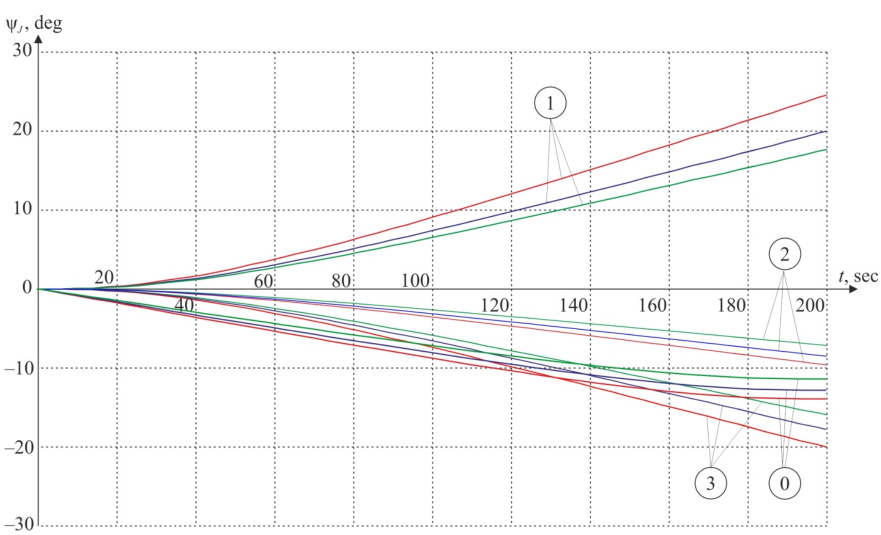

Fig. 5. Diagrams of dependency of yaw angle of the ship, type Supply Vessel, length 76 m, in the time function: 0—3 — numbers of appropriate configurations (16)—(19): ——— — mutial perpendicular axis location of the main and auxiliary pods with unchanged values of step ratios and thrusts coefficients; ——— — mutial perpendicular axis location of the main and auxiliary pods with regulated values of step ratios and thrusts coefficients; ——— — the optimal location of the axes of the main and auxiliary pods with values of step ratios and thrusts coefficients that meet the criterion of minimum change in the XY-coordinates of the ship

By analysing the diagrams in Fig. 4, 5, it is possible to make a conclusion that the optimal from the point of view of the ship moving in the XY-plane is the configuration thrusters #2, which is determined by the matrix (18).

6. Conclusions

1. The proposed approach to the design of DSS SPP CPC allows predicting total quantity and the type of thrusters and pods, power system of electric motors with possibility of multiple design changes even in the presence of minimal data of the existing project and can be used practically for any type of the ship. DSS also allows upgrading various types of vessels for their adaptation to dynamic positioning mode and gives the possibility to synthesize recommendations for thrusters developers, controllers and power systems for ships, working in a mode of dynamic positioning. This is achieved due to the fact that the proposed approach is based on the cognitive (in sinergy with engineering) research process of decision-making that includes gradual improvement of the data that comes from the study of a particular operational mode of the vessel operation. Its characteristic difference is the application of the method of reciprocal implementation of the characteristic spatial vectors of energy processes in SPP and hydrodynamic processes in CPC. Due exactly to this difference, the developed DSS does not require the application of the criteria of similarity and allows multiple analysis of the SPP and CPC structure at minimal original data.

2. The ability to change thrusters settings, in particular: the values of the step ratios, thrusts coefficients and the location of the axes of the main and auxiliary pods, for a specific ship greatly expanded the use of the approach from the point of view of acceleration of convergence of synthesized DMI-models of ships, and for a given speed of pod rotation, traction, torque and stepper attitude allowed establishing that the coefficient of traction (thrust) increases with the change of mutual thrusters location relative to one another and the diametral plane of the ship.

3. It was also found that the correlation of thrusts coefficient is better correlated to the coefficients of power than to the step coefficients of pod, which gives the reason to think about the opportunity to improve the energy efficiency of SPP CPC in operational modes and include obtained results to the database for other similar DSS to provide developers and researchers with the necessary information for creating new concepts of SPP CPC or to modify existing ones.

Experimental research for applied configurations of thrusters is planned to be performed on a physical model of CPC [33–36].

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