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DYNAMIC SIMILARITY OF ELECTRIC SHIPS' PROPULSIVE COMPLEXES

Shumylo O.M.[1], **Yarovenko V.O.**[2], **Zaritska O.I.**[3]
[1]Ph.D, Professor at the Department of Ship Power Plants and Technical Operation,
Odessa National Maritime University, Odessa, Ukraine,
ORCID ID: 0000-0003-0574-1954
[2]Dr. of Eng., Head of the Department of Operation
of Ship Eelectrical Equipment and Automation,
Odessa National Maritime University, Odessa, Ukraine,
ORCID ID: 0000-0003-3183-6583
[3]Ph.D, Associate Professor at the Department of Operation
of Ship Eelectrical Equipment and Automation,
Odessa National Maritime University, Odessa, Ukraine,
ORCID ID: 0000-0002-8530-1106

Summary

The purpose of the research *is to develop methods for analyzing the maneuvering modes of ship propulsion systems based on the theory of dynamic similarity.* ***Methodology.*** *On maneuvers, all components of the complexes operate in transient modes, significantly influencing each other, therefore, the analysis of the operation modes of any component is considered in unity with the others. The necessity of transition to generalized mathematical models is substantiated. The dynamic similarity criteria are found. There is a possibility of broad generalization of research results.* ***Results.*** *A mathematical model and a method for calculating the transient modes of electric ships'propulsion complexes have been developed. The generalized dimensionless parameters of the complex are found. The expediency of conducting research in relation to these parameters and dynamic similarity criteria are substantiated. A technique for conducting research using the provisions of dynamic similarity theory has been developed. The possibilities of using the technique are illustrated by the example of calculating the maneuvering characteristics and assessing the loads on the electric power plant when the electric ship enters circulation. The possibility of using the developed technique in the search for ways to improve complexes' maneuverability is shown.* ***Scientific novelty.*** *The use of dynamic similarity criteria and generalized dimensionless parameters makes it possible to cover a large class of ships in research. Electric ships with equal values of similarity criteria and equal values of generalized parameters will have the same laws of change of regime indicators and equal values of maneuvering quality indicators. It becomes possible to level the influence of inaccuracies in the assessment of external factors on the results of research.* ***Practical significance.*** *The recommendations, analytical ratios, diagrams for assessing the quality of maneuvering, developed on the basis of the theory of similarity, cover a whole series of electric ships and are ready for use. They contribute to the construction of electric ships with predictable maneuvering properties. Bible 15, Tab. 2, Fig. 1.*

Key words: *electric ship's propulsion complex, dynamic similarity, analysis of maneuvering modes.*

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ДИНАМІЧНА ПОДОБА ПРОПУЛЬСИВНИХ КОМПЛЕКСІВ ЕЛЕКТРОХОДІВ

Шумило О.М.[1], Яровенко В.О.[2], Зарицька О.І.[3]
[1]к.т.н., професор кафедри суднових енергетичних установок і технічної експлуатації,
Одеський національний морський університет, Одеса, Україна,
ORCID ID: 0000-0003-0574-1954
[2]д.т.н., професор, завідувач кафедри експлуатації суднового електрообладнання
і засобів автоматики,
Одеський національний морський університет, Одеса, Україна,
ORCID ID: 0000-0003-3183-6583
[3]к.т.н., доцент кафедри експлуатації суднового електрообладнання і засобів автоматики,
Одеський національний морський університет, Одеса, Україна,
ORCID ID: 0000-0002-8530-1106

Анотація

Мета досліджень *у розробці методів аналізу маневрених режимів суднових пропульсивних комплексів на основі теорії динамічної подоби.* ***Методика.*** *На маневрах всі складові комплексів працюють на перехідних режимах, істотно впливаючи одна на одну, тому аналіз режимів роботи будь-якої складової розглядається в єдності з іншими. Обґрунтовано необхідність переходу до узагальнених математичних моделей. Знайдено критерії динамічної подоби. З'являється можливість широкого узагальнення результатів досліджень.* ***Результати.*** *Розроблено математичну модель та метод розрахунку перехідних режимів пропульсивних комплексів електроходів. Знайдено узагальнені безрозмірні параметри комплексу. Обґрунтовано доцільність проведення досліджень стосовно цих параметрів та критеріїв динамічної подоби. Розроблено методику проведення досліджень із використанням положень теорії динамічної подоби. Проілюстровано можливості використання методики на прикладі розрахунку маневрених характеристик та оцінки навантажень на електроенергетичну установку при виході електроходу на циркуляцію. Показано можливість використання розробленої методики при пошуках шляхів покращення маневреності комплексів.* ***Наукова новизна.*** *Використання критеріїв динамічної подоби та узагальнених безрозмірних параметрів дає можливість охопити дослідженнями великий клас суден. Електроходи з рівними значеннями критеріїв подоби та рівними значеннями узагальнених параметрів матимуть однакові закони зміни режимних показників та рівні значення показників якості маневрування. З'являється можливість нівелювання впливу неточності щодо оцінки зовнішніх чинників на результати досліджень.* ***Практична значимість.*** *Розроблені на основі теорії подібності рекомендації, аналітичні співвідношення, діаграми для оцінки показників якості маневрування охоплюють цілі серії електроходів, готові до застосування, та сприяють побудові електроходів із заздалегідь прогнозованими маневреними властивостями. Бібл. 15 табл. 2, рис. 1.*

Ключові слова: *пропульсивний комплекс електрохода, динамічна подоба, аналіз маневрених режимів.*

Relevance of research and problem statement. Electric propulsion is a stable trend in the development of modern shipbuilding. Its most important advantage over the traditional ship propeller drive is the ability to provide high maneuverability for ships that are equipped with power plants of this type. It is these propulsion systems that ensure the safety of maneuvering operations. If, at the same time, the complex also includes active propulsion control means, the vessel’s maneuvering properties can hardly be overestimated.

Propulsion electric power plants, most often, are designed on the basis of asynchronous frequency-controlled propulsion motors. They can be made both according to the classical version, and according to the version of the Azipod propulsion and steering complex (in this case, the rudder is not needed). In turn, propulsion electric power plants are part of a single ship electric power system that provides power to both the electric propulsion system itself and general ship consumers of electricity. Thus, the ship's propulsion complex is a complex system that combines many components with the most diverse physical processes occurring in them. An enlarged block diagram of such a propulsion complex is shown in Fig. 1.

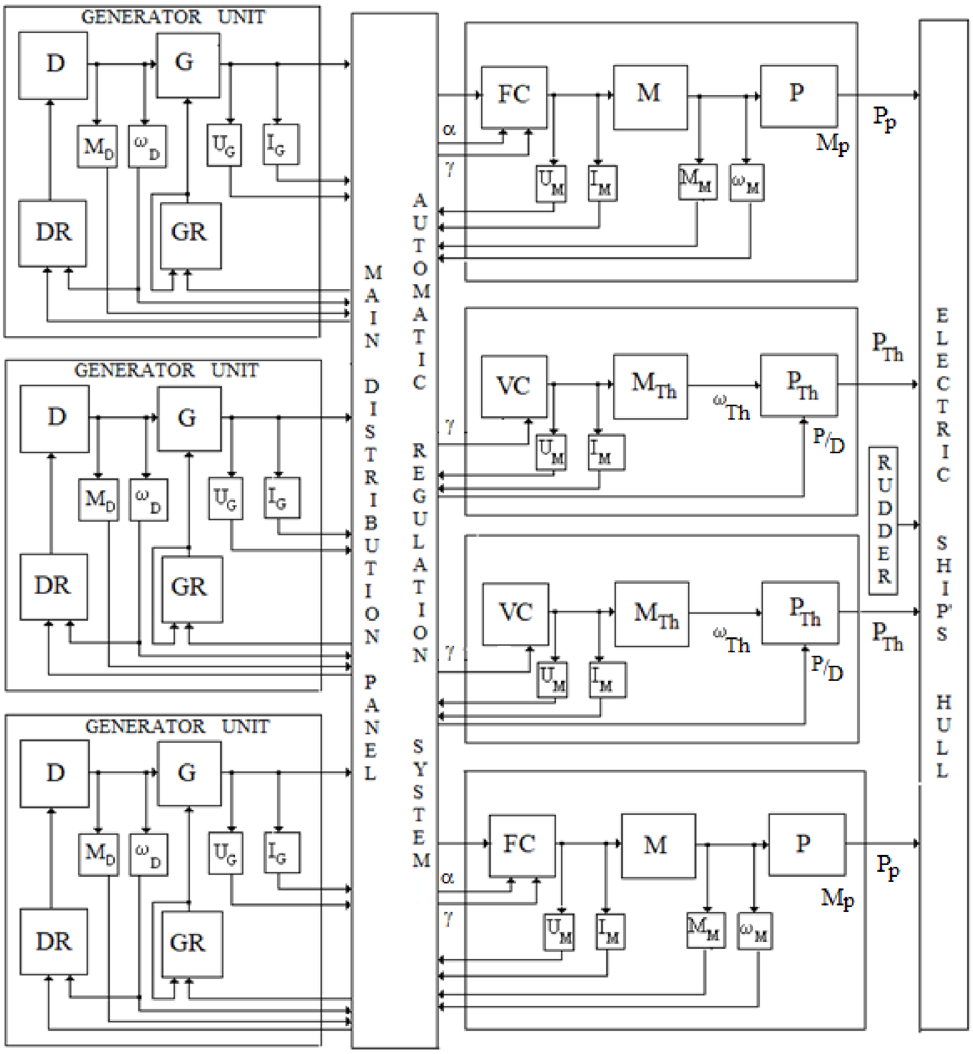

Fig. 1. Structural diagram of the electric ship’s propulsion complex

The complex includes: heat engines D with frequency rotation regulators DR; synchronous generators G with voltage regulators GR; frequency converters FC; asynchronous propulsion motors M; propellers P; thrusters' voltage converters VC, propulsion motors M_{Th} and propellers P_{Th}; rudder R and hull. (In each specific case, individual elements may be absent in the block diagram.)

When maneuvering the ship, all these components operate almost continuously in transient modes, while exerting a significant influence on each other. That is why the analysis of the maneuvering operation modes of any element of the ship's propulsion complex must be considered in unity with all other components.

The issues of designing modern electric ships with high maneuverability and the tasks of improving the control of propulsion electric power plants of ships in operation are currently very relevant. Moreover, the need to assess the maneuverability of newly built electric ships arises already at the initial stages of their design or modernization, and improving the efficiency of the maneuvering operations of existing ships is undoubtedly relevant at any stage of their life cycle.

The State of the Issue. The methods of mathematic modeling of electric ships' transient and steady operation modes during maneuvers are widely used in the process of designing and developing recommendations to find best ways of controlling the complexes. At the same time, there arise a number of problems, the solution of which results in essential difficulties.

The first problem is that in the vast majority of studies, the propulsion electric power installation is considered [1, 2] in isolation from a single ship propulsion complex. Transient processes in each element of the complex are described by mathematical equations in more or less detail, depending on the goals of the research. As a rule, such a description is based on the assumption that the rest of the objects that make up the complex operate in a steady state, and the influence of the environment is taken into account approximately [3, 4, 5]. However, the mathematical description of any real object corresponds only more or less approximately to the real processes occurring in the object. Insufficient mathematical base as the basis for describing the interaction of an object with the environment significantly reduces the reliability of the results obtained. The results of experimental studies are most often used to obtain reliable information about these processes [3]. However, such tests are expensive, and represent a special case (or special cases). The validity of the distribution of these results on other objects (even on objects of the same type) is problematic and is often associated with a low degree of accuracy.

At the same time, when analyzing complex systems, which undoubtedly include the ship's propulsion complex, there inevitably arises the question of the necessary and sufficient degree of accuracy in describing the processes occurring in each component of this complex. This accuracy, first of all, depends on the stated goals and criteria for assessing the quality of the operation of the complex, as such, and its components, in particular. And each of the factors influencing the behavior of the complex can be significant for some quality criteria and completely insignificant for others. This situation becomes even more complicated when the system includes objects that are completely different in nature of the physical processes occurring in them. In such cases, the task arises in leveling (reasonably) the influence of inaccuracies in the assessment of certain parameters on the calculation results.

In the vast majority of cases, studies of the electric ships' maneuverability relate to individual devices of the ship's propulsion complex [6, 7] and to specific maneuvers [8, 9, 10]. Their purpose is to build the trajectory of the vessel motion, assess the loads on certain components of the complex, create and construct simulators for ship complexes, etc. With this approach, each individual component is separated from a single propulsion complex and is considered on the assumption that all other parts operate in a steady state. However, such an assumption is valid only for steady-state operating modes, and, as for transient ones, it leads to significant inaccuracies.

Second problem. The goal and end result of any scientific research is the possibility of generalizing the results obtained and the prospects for predicting the behavior of the objects under study (and objects similar to them), at least in typical and in the most typical situations. Research should cover the widest possible class of objects (the widest possible class of ships). They should contribute both to the creation of new electric ships with predetermined properties, and to an increase in the efficiency of the operation of already existing ones.

The solution of all these problems is possible on the basis of the theory of dynamic similarity. Considering a dynamically similar ship propulsion complex, identifying the criteria of dynamic similarity and complex generalized parameters, we can:

– cover with the results of research a wide class of ships of the type under consideration;

– neutralize the influence of a low degree of accuracy in determining a number of physical parameters and interactions on the final results of research and on the recommendations being developed (they can be easily corrected after clarifying the values of these parameters and interactions);

– develop, in the form of ready-made analytical expressions or diagrams, recommendations for the design and control of propulsion systems with predictable performance indicators.

The development of a methodology for constructing such studies is the **goal of this work.**

Analysis of dynamically similar propulsion complexes. As can be seen from Fig. 1, the complex includes a large number of components with different physical principles of operation. These parts are connected to each other by an automatic control system with a large number of feedbacks. The main parameters connecting the power units and control signals are: M_D and ω_D – torque and angular velocity of the heat engine; U_G and I_G – generator voltage and current; U_M, I_M, M_M and ω_M – voltage, current, torque and angular speed of rotation of the propulsion propelling motor; M_P and P_P – propeller torque and thrust; M_{Th}, ω_{Th}, P_{Th} – torque, angular velocity and propeller thrust of the thrusters; α and γ – the relative frequency and voltage at the output of the converters; P/D – the pitch ratio of the thruster propeller.

Even the general view of the block diagram gives an idea of the degree of complexity of the mathematical model that describes the transient operation modes of the complex. One of its variants, as applied to the classical layout of a propulsion electric power plant, is given in [12]. This model includes a large number of differential and algebraic equations. It follows from it that hundreds of parameters influence the nature of the course of transient processes, the indicators of the maneuvering quality. These are both the design parameters of the propulsion system, and the parameters determined by the conditions for performing maneuvers, and the parameters of control actions. Such a situation does not allow us to assess correctly the degree of influence of each parameter separately and also does not allow assessing the degree of influence of the effects of these parameters' interactions. Moreover, it is impossible to predict the influence of these parameters on the maneuvering quality indicators, and it is impossible to predict electric ships' maneuvering characteristics, as well.

It should also be remembered that in the process of studying maneuvering modes, the results of any calculation performed in relation to any particular electric ship are only partial. This is the solution of a separate specific problem (calculation of any maneuver) in relation to a specific electric ship in certain external conditions and in a specific situation. The scientific value of such calculations is not great. It is worth changing any design parameter of the electric ship or the conditions for performing the maneuver, and the result of the calculation will be different.

To give generality to the results of the analysis, one should use the concept of an approximate dynamically equivalent complex [13] and reduce the model to dimensionless units. This will allow converting the regime indicators to relative units and identifying the dimensionless parameters of the electric ships' propulsion complexes.

To do this, we introduce the concept of the basic operation mode and, accordingly, the basic values of the mode indicators. As such (they are marked with the index "0"), we take the values corresponding to the operation of the complex in the nominal steady state, when the vessel is moving in free, deep, calm water in a direct course. Then the relative values of regime indicators will be defined as the ratio of the current values to the base values. They will be marked by a dash symbol. For example, the relative electromagnetic moment of the generator

$$\overline{M_G} = \frac{M_G}{M_{G0}}. \tag{1}$$

Such transformations are carried out with all regime indicators of the complex. The exception is relative time. It is defined differently:

$$T = \frac{v_0}{L} t, \tag{2}$$

where v_0 – is the speed of the ship, L – is the length of the ship, t – is the current time.

Below, as an example, the basic equations obtained, in this way, from the generalized mathematical model of transient modes are presented here. These are the equations describing the inertial components of the propulsion system [12].

The equation of the generating set motion:

$$\frac{d\overline{\omega_D}}{dT} = N_D\left(\overline{M_D} - \overline{M_G}\right), \tag{3}$$

where N_D – is a dimensionless parameter

$$N_D = \frac{M_{D0} L}{J_D \omega_{D0} v_0}; \tag{4}$$

J_D – is the moment of inertia of the engine and generator reduced to the heat engine shaft;

The dimensionless parameter N_D – is a dynamic similarity criterion of the system: heat engine – synchronous generator. Complexes with equal values of this criterion will have the same (in relative terms) laws of change of regime indicators in relative time.

Synchronous generator excitation current

$$\frac{d\overline{I_f}}{dT} = N_f\left(K_{f1}K_{Uq}\overline{U_q} + K_{f2}K_{Id}\overline{I_d} - K_{f3}K_U\left(\overline{U_G} - \left(1 - \Delta\overline{U_{H1}}\right)\right) - \overline{I_f}\right), \tag{5}$$

where N_f – is the dynamic similarity criterion

$$N_f = \frac{LU_{f0}}{L_f I_{f0}\nu_0}; \tag{6}$$

L_f – is the inductance of the excitation winding; U_f and I_f – are the voltage and current of the excitation winding; $\Delta\overline{U_{H1}}$ – is the voltage difference between generators operating in parallel; K_{f1}, K_{f2}, K_{f3} – are gain coefficients of the automatic control system $\overline{U_d}$ and $\overline{U_q}$, $\overline{I_d}$ and $\overline{I_q}$ – are the generator voltage and current according to internal *d-q* coordinates; K_{d1}, K_{q1}, $K_{q2} = 1$, K_{Uq}, K_{Id}, K_U – are the generalized dimensionless parameters.

The equation of motion of the propulsion motor

$$\frac{d\overline{\omega_M}}{dT} = N_M\left(\overline{M_M} - \overline{M_P}\right), \tag{7}$$

where: N_M – is the dynamic similarity criterion

$$N_M = \frac{M_{M0}L}{J_M\omega_{M0}\nu_0}; \tag{8}$$

J_M – is the moment of inertia of the propulsion motor.

Equations of an electric ship motion in the *GXYZ* coordinate system associated with the ship:

$$\frac{d\overline{\nu_X}}{dT} = C_{\lambda 2}\overline{\nu_Y}\,\overline{\Omega_Z} + N_X\left\{\sum_J K_{Pj}\overline{P_{ej}} - C_{RX}\beta_{RP}\overline{\nu^2} - \overline{R_X}\right\}; \tag{9}$$

$$\frac{d\overline{\nu_Y}}{dT} = -\frac{1}{C_{\lambda 2}}\overline{\nu_X}\,\overline{\Omega_Z} + \frac{N_X}{C_{\lambda 2}}\left\{\sum_J K_{Pj}\alpha_{jz}\overline{P_{ej}} + C_{RY}\beta_{RP}\overline{\nu^2} \pm \sum_h k_h\overline{P_{Thh}} - \overline{R_Y}\right\}; \tag{10}$$

$$\frac{d\overline{\Omega_Z}}{dT} = -\frac{N_\Omega}{N_X}C_{\lambda 21}\overline{\nu_X}\,\overline{\nu_Y} + N_\Omega\left\{\sum_j K_{Pj}h_{Pj}\overline{P_{ej}} + C_{RY}\overline{X_R}\beta_{RP}\overline{\nu^2} \pm \sum_h k_h\overline{P_{Thh}}\,\overline{h_h} + \left(\overline{M_{PZ}} - \overline{M_{DZ}}\right)\right\}, \tag{11}$$

where N_X and N_Ω – are the dynamic similarity criteria

$$N_X = \frac{L\sum K_{Pj}P_{ej0}}{(m + \lambda_{11})\nu_0^2}; \tag{12}$$

$$N_\Omega = \frac{L^3\sum K_{Pj}P_{ej0}}{2(J_Z + \lambda_{66})\nu_0^2}; \tag{13}$$

P_{ej} and K_{Pj} – are the useful thrust of the propeller and its share in the total flow, respectively; $\sum_h k_h\overline{P_{Thh}}$ – is the total thrust of thruster propellers; $\sum_h k_h\overline{P_{Thh}}\,\overline{h_h}$ – is the total torque of the thruster propellers relative to the ship's center of gravity. $\overline{R_X}$ and $\overline{R_Y}$ – are the longitudinal and transverse components of water resistance to the vessel motion; ($\overline{M_{PZ}} - \overline{M_{DZ}}$) – is the moment of resistance to the turn of the vessel; X_R – is the distance from the center of the coordinate system to the rudder; ρ – is water specific density; λ_{11} and λ_{22} – are the added water masses along the *X* and *Y* axes; J_Z – is the ship's moment of inertia when rotating around the Z axis; λ_{66} – is the added moment of water inertia; β_{dr} – is the drift angle; $\overline{P_{Thh}}$, $\overline{h_h}$ and k_h, – are the relative thrust, its shoulder and the proportion of the thrust of the corresponding thruster at the maximum pitch ratio in the total thrust of the propulsive propellers; generalized dimensionless parameters:

$$C_{\lambda 2} = \frac{m + \lambda_{22}}{m + \lambda_{11}} \; ; \tag{14}$$

$$C_{RX} = \frac{\mu_{rx} \frac{\rho}{2} v_0^2 S_C \left(1 - \psi\right)^2}{\sum K_{Pj} P_{ej0}} \; ; \tag{15}$$

$$C_{RY} = \frac{\mu_K \frac{\rho}{2} v_0^2 S_C \left(1 - \psi\right)^2}{\sum K_{Pj} P_{ej0}} \, . \tag{16}$$

The control system in the general case forms:

– two control actions on the frequency converter – by frequency α and by voltage γ;

– voltage control signal γ to the thruster drive voltage converter;

– control signal by propeller pitch to the mechanism of change of thruster propeller pitch;

– a control signal for the angle of the rudder blade.

A complete mathematical model is given in [14]. It allows for a comprehensive analysis of the propulsion complex maneuvering modes. During the calculation, the current values of the main regime indicators of its components are calculated.

When converting the original model into a system of dimensionless units, the criteria for dynamic similarity and generalized dimensionless parameters of the propulsion complex were identified. These are the parameters of the system "heat engines – propulsion electric plant – propellers – rudder – ship's hull". It is these parameters that determine the current values of the relative performance indicators of all the components of the complex and affect the numerical values of the main indicators of the quality of maneuvering. Relationships for calculating these parameters and similarity criteria are given in [14]. All further studies of the behavior of electric ships during maneuvers should be carried out in relation to these parameters – in fact, to some "generalized" parameters, which include in a certain combination both the design parameters of the complex and the parameters of the environment. Complexes with equal values of parameters will have the same laws of change in time of the main regime indicators. The transition to dimensionless parameters greatly reduces the variable parameters in the study of maneuvering modes.

The solution to the second problem, identified for research purposes, involves covering the widest possible class of vessels, with the possibility of expanding and generalizing the results of the study. To this end, it is necessary to calculate the numerical values of the identified generalized dimensionless parameters for existing ships (covering as many electric ships as possible) and determine the range of their values. Having considered the behavior of the complexes in the entire range of changes in the values of these parameters, it is possible to cover all vessels of the type under consideration by research.

Evaluation of the electric ships' maneuvering characteristics is carried out according to certain quality indicators. First of all, these are the inertial-braking characteristics, the controllability of ships and the load on their electric power systems. In [12], a set of such indicators is proposed. They fully cover each component of the electric power plant and the entire electric ship as a whole. However, despite the transition to a system of dimensionless units, the number of generalized parameters still remains large. This complicates the analysis of maneuvering modes, and if we take into account that the number of maneuvering quality indicators themselves is more than forty [12], the solution of the set tasks becomes unfeasible.

The way out of this situation is to identify the parameters that significantly affect the indicators of the quality of maneuvering. In other words, from the set of parameters q_i, $i=1,...,n$, it is necessary to select a subset of parameters $q_j, j=1,...,p\,(p<n)$, the deviation of which from the calculated values Δq_j determines the main part of the increment of quality indicator $J(\Delta q_j)\approx J(\Delta q_i)$. The scatter of the values of the remaining parameters does not have a significant effect on the indicator under study, and changes in their values can be ignored.

The solution of such problems, as a rule, is carried out by the methods of screening experiments, which makes it possible to rank all the parameters of the complex and the effects of parameter interactions on the values of quality indicators. At the same time, it should be taken into account that for each quality indicator there will be its own set of significant parameters and significant effects of parameter interactions.

All further studies are carried out taking into account changes in these very significantly influencing parameters.

Let us illustrate the possibilities of the considered approach in the analysis of the electric ships' maneuvering properties. As an example, below are the results of an analysis of the maneuvering characteristics of an electric vessel when it enters circulation. A ship with a classic version of the layout of the electric power plant is considered. In [15], simplified analytical dependences of the main indicators of the quality of maneuvering on the similarity criteria and generalized parameters of the complex were developed. These dependences characterize the entry of the vessel into circulation:

– duration of circulation $T_{man.}$ and its evolutionary period T_{ev}

$$T_{man.} = 36{,}672 + 13{,}094N_X - 7{,}375C_{M16} + 3{,}484C_{65} + 4{,}563C_{61} - 4{,}344C_{\lambda 21}$$
$$-1{,}891N_XC_{M16} + 2{,}281N_XC_{65} + 3{,}953N_XC_{61} - 3{,}234N_XC_{\lambda 21} - 3{,}265C_{RY} + 1{,}867C_{M16}C_{\lambda 21}; \quad (17)$$

$$T_{ev} = 14{,}578 - 5{,}875N_X - 2{,}469C_{M16} - 0{,}782C_{61} + 1{,}141N_XC_{M16} - 1{,}106C_{22}; \quad (18)$$

– fuel costs for the maneuver G_{man}

$$G_{man}. = 43{,}141 + 11{,}019N_X - 6{,}725C_{M16} + 3{,}533C_{65} + 4{,}693C_{61} - 4{,}636C_{\lambda 21} -$$
$$- 3{,}251C_{RY} - 2{,}848N_XC_{M16} + 2{,}3N_XC_{65} + 4{,}038N_XC_{61} - 3{,}138N_XC_{\lambda 21}; \quad (19)$$

– relative decrease in the speed of the ship in steady circulation Δv_{cir};

$$\Delta v_{cir} = 0{,}375 - 0{,}296N_X - 0{,}019C_{65} - 0{,}021C_{61} - 0{,}03C_{\lambda 21}; \quad (20)$$

– relative diameter of steady circulation D_{cir}

$$D_{cir} = 6{,}81 + 4{,}909N_X + 0{,}885C_{65} + 1{,}224C_{61} - 1{,}21C_{\lambda 21} - 0{,}806C_{RY} +$$
$$+0{,}69N_XC_{65} + 1{,}045N_XC_{61} - 0{,}815N_XC_{\lambda 21} - 0{,}422C_{M16}C_{\lambda 21}. \quad (21)$$

Here: N_X; C_{M16}; C_{22}; C_{65}; C_{61}; C_{21}; $C_{\lambda 21}$; C_{RY} – are generalized dimensionless parameters of the electric ship's propulsion complex:

$$N_X = \frac{LP_{e0}}{(m+\lambda_{11})v_0^2};\quad C_{22} = \frac{c_2 \cdot \frac{\rho}{2} v_0^2 F_H}{\sum K_{Pj} P_{ej0}};$$

$$C_{M16} = \frac{\beta_{M0}}{r_M'^2}\left[\left(b_M^2 + c_M^2\alpha_0^2\right) + \left(d_M^2 + e_M^2\alpha_0^2\right)\frac{r_{2M}'^2}{\beta_{M0}^2} + 2r_{1M}\alpha_0 \frac{r_{2M}'}{\beta_{M0}}\right];$$

$$C_{\lambda 21} = \frac{2(\lambda_{22} - \lambda_{11})}{m + \lambda_{11}};\quad C_{21} = \frac{0,5C_Y^{\beta}\frac{\rho}{2}v_0^2 F_{\text{Н}}}{P_0};\quad C_{61} = \frac{2m_1\frac{\rho}{2}v_0^2 F_{\text{Н}}}{P_0};$$

$$C_{65} = \frac{2\left[0,739 + 8,7\frac{T}{L}\right]C_{m0}^{\omega}\frac{\rho}{2}v_0^2 F_{\text{Н}}}{P_0};\quad C_{RY} = \frac{\mu_K \frac{\rho}{2} v_0^2 S_R (1-\psi)^2}{\sum K_{Pj} P_{ej0}},$$

where ω_{M0} и $\omega_{1M\text{н}}$ – are angular speeds of rotation of the propulsion motor and the stator magnetic field at rated frequency; β_{M0} – is absolute slip of the *M* rotor; α_0 – is *M* relative voltage frequency; r_{1M} and $r_{2M'}$ – are stator active resistance and the reduced active resistance of the *M* rotor; b_M, c_M, d_M, e_M – are constant coefficients of the frequency-controlled induction motor; C_Y^{β} – is coefficient of the positional hydrodynamic force acting on the ship's hull; F_H – is the reduced area of the submerged part of the ship's center plane; ρ – is specific water density; S_R – is the reduced area of the rudder blade; m^1 – is coefficient of the positional resistance moment; C^{ω}_{m0} – is coefficient of damping resistance moment.

These dependencies were obtained using the method of full factorial experiment. The ranges of changes of parameter values and similarity criteria (from minimum to maximum) are given in Table 1.

Table 1

Ranges of changes of parameter values

Parameter	Value ranges			
	Minimum	Average	Maximum	Project
N_X	0,06	0,13	0,20	0,132
C_{M16}	4,16	7,15	14,05	14,127
C_{21}	2,7	3,4	4,1	3,372
C_{61}	2,8	3,5	4,2	3,564
C_{22}	16	21	26	21,19
C_{65}	3	4	5	4,074
Cl	0,55	0,7	0,85	0,736
C_{RY}	1,1	1,5	1,9	1,532

Having calculated the numerical values of these parameters using the above ratios, it is possible to estimate the main parameters of the ship's circulation motion using ready-made simple analytical dependencies (17)-(21). Let's consider this on the example of an electric ship project with an electric power plant based on frequency-controlled propulsion motors.

The main characteristics of the vessel project: length according to design waterline 52 m; width 15 m; draft 4 m; displacement 1700 tons; power of the main engines 2200 kW; movement speed, at the rated power of the propulsion electrical installation, 7 m/s.

The power plant includes: two diesel generator sets, each of which contains a diesel engine with an effective power of 1100 kW at 750 rpm and a generator with a power of 100 kW at 750 rpm; frequency converters; two asynchronous propulsion motors.

Propulsion motors have the following main parameters: power 1000 kW; stator current 1100 A; power factor 0.835; torque 10670 Nm; angular velocity of rotation 93.67 s^{-1}.

Basic winding data: stator active resistance 0.00419 Ohm; stator reactance 0.0879 Ohm; rotor reduced active resistance 0.0359 Ohm; rotor reduced reactance 0.1319 Ohm; resistance reduction factor 34.336; magnetizing reactance 1.503 ohms.

The numerical values of the significantly influencing dimensionless parameters of the project under consideration, calculated according to the above ratios, are presented in the corresponding column in Table 1.

The results of calculations, according to the relations (17)-(21) of the selected indicators of the quality of the maneuver, are given in Table 2.

Table 2

The main indicators of the quality of the maneuver

Quality indicators	Analytical dependencies	Exact method	Error, %
1. Circulation time – T_{man}	20,5	22,521	9,8
2. Evolutionary period of circulation – T_{ev}	13	13,388	3
3. Fuel costs for the maneuver – G_{man}	30,5	31	1,5
4. Reducing the speed of the vessel on the circulation – Δ	0,55	0,455	17,3
5. Relative circulation diameter – D_{cir}.	3,75	4,13	10

Calculations of these indicators, performed using a complete mathematical model, gave the results presented in the corresponding column of Table 2. It also shows the error in the results obtained from analytical dependencies compared to those obtained from the full mathematical model.

The given example clearly illustrates the possibilities of using the theory of dynamic similarity in solving problems of analyzing the dynamics of electric ships' propulsion complexes. In particular, by calculating the basic dynamic similarity criteria and dimensionless parameters of the complex by the simplest ratios, it is possible to estimate in the first approximation the quality indicators of maneuvering of electric ships' propulsion complexes.

The use of the concepts of dynamic similarity makes it possible not only to evaluate the main quality indicators of the maneuver execution, but also to find possible ways to improve them. Let us illustrate these possibilities by the example of the analysis of quality indicators characterizing the behavior of an electric power plant during the maneuver "acceleration of the vessel – entry into circulation".

As the main indicators for this maneuver, the following corresponding analytical dependencies were selected and obtained:

– relative change in the angular velocity of rotation of propulsion motors and propellers

$$\omega\Delta_M = 0{,}076 - 0{,}051N_X - 0{,}029C_{M16} - 0{,}004C_{61} + 0{,}006C_{\lambda 21} + 0{,}004C_{RY+} + 0{,}016N_X C_{M16}; \quad (22)$$

– relative change in heat engine power

$$\begin{aligned}\Delta P_D = {} & 0{,}227 - 0{,}129N_X + 0{,}131C_{M16} - 0{,}026C_{22} - 0{,}118N_X C_{M16} - 0{,}026C_{M16}C_{65} - \\ & - 0{,}02C_{M16}C_{61} + 0{,}014C_{21}C_{65} + 0{,}015C_{21}C_{61} - 0{,}015C_{21}C_{\lambda 21} + 0{,}016C_{65}C_{61} - \\ & - 0{,}014C_{65}C_{\lambda 21} - 0{,}014C_{61}C_{\lambda 21}; \quad (23)\end{aligned}$$

– relative change in propulsion motor current

$$\Delta I_M = 0{,}205 - 0{,}138N_X + 0{,}116C_{M16} - 0{,}012C_{65} - 0{,}011C_{61} - 0{,}013C_{\lambda 21} - \\ - 0{,}09N_X C_{M16} - 0{,}011C_{22}; \tag{24}$$

– relative change in propulsion motor torque

$$\Delta M_M = 0{,}147 - 0{,}097N_X + 0{,}121C_{M16} - 0{,}01C_{65} - 0{,}008C_{61} + 0{,}009C_{\lambda 21} - \\ - 0{,}01C_{22} - 0{,}088N_X C_{M16}\,. \tag{25}$$

When comparing the last three indicators, attention is drawn to the identity of the nature of the dependence of ΔP_D, ΔI_M and ΔM_M indicators on the parameters of the complexes. This corresponds to the physical relationship of the processes occurring in the power plant – with an increase in the load on the propulsion motor M_M, the propulsion motor current I_M and the heat engine power P_D increase accordingly, and approximately equally. At the same time, the degree of an increase in the heat engine power – the "last" link in this power chain – begins to be more significantly affected by the effects of the parameter interactions that characterize the electric ship's hull.

The main parameters affecting the performance of the power plant $\Delta\omega_M$, ΔP_D, ΔI_M, ΔM_M are the power-to-weight ratio of the N_X electric ship (contribution – 27...67%), and the dimensionless parameter of propulsion motors – C_{M16} (contribution 16...83%). In addition to them, these indicators are significantly affected by the parameters determined by the coefficients of the hydrodynamic forces of resistance to the movement of the ship C_{22}, C_{61} and C_{65}. Basically, the quality indicators of the M operation are linearly dependent on the parameters of the complexes. The performance of the other components of the complex is also significantly affected by the effects of parameter interactions, and these effects are commensurate with the influences of the parameters themselves.

Conclusions.

1. The use of the theory of dynamic similarity helps to increase the efficiency of design processes and the results of the search for the best operating modes for electric ships' propulsion complexes. The identification of dynamic similarity criteria and generalized dimensionless parameters of propulsion complexes makes it possible to cover a large class of ships with research. It seems possible to level the influence of inaccuracies in the assessment of external factors on the regime indicators of the complex.

2. Opportunities are opening up to generalize the results of research. Complexes with equal values of similarity criteria and generalized parameters will have the same laws of change in regime indicators and equal values of performance indicators. The identification of significant parameters and significant interaction effects allows reducing the number of necessary experiments by a factor of ten in the course of further research. Visualization appears in assessing the influence of one or another parameter on regime indicators, and also the perception of the physical nature of the processes under study is facilitated.

3. The transition to generalized dimensionless parameters makes it possible to carry out parametric optimization and search for optimal control laws for propulsion systems during maneuvers. This contributes to the construction of electric ships with predictable maneuvering properties.

REFERENCES

1. Hansen J. F. Modeling and Control of Marine power System: Thesis for the Degree of Philosophy Doctor / J. F. Hansen. Norwegian University of Science and Technology, 2008. 119 p.
2. Radan D. Integrated Control of Marine Electrical Power System: Thesis for the Degree of Philosophy Doctor / D. Radan. Norwegian University of Science and Technology, 2008. 231 p.
3. Yukun Feng, Zuogang Chen, Yi Dai, Ping Wang. An experimental and numerical investigation on hydrodynamic characteristics of the bow thruster. Ocean Engineering, 2020, vol. 209(8):107348. doi: 10.1016/j.oceaneng.2020.107348.
4. Teresa Abramowicz-Gerigk, Miroslaw K. Gerigk. Experimental study on the selected aspects of bow thruster generated flow field at ship zero-speed conditions. Ocean Engineering, 2020, vol. 209(92):107463. doi: 10.1016/j.oceaneng.2020.107463.
5. Liu Hui, Feng Yukun, Chen Zuogang, Dai Yi, Tian Ximin. Numerical Study of Pressure Fluctuation for Bow Thruster. Journal of Shanghai Jiaotong University, 2017, vol. 51(3), pp. 294-299. doi: 10.16183/j.cnki.jsjtu.2017.03.007.
6. Ionut Cristian Scurtu, Valentin Oncica. Combined CFX and Structural Simulation for Bow Thrusters Loading under Operating Conditions. Journal of Physics Conference Series, 2018, vol. 1122(1):012024. doi: 10.1088/1742-6596/1122/1/012024.
7. Sardono Sarwito, Semin Semin, Muhammad Badrus Zaman, Kamarul Hawari Ghazali. Unbalanced Voltages of Bow Thruster Motor Performance in the Ship Using Simulation. International Review of Electrical Engineering (IREE) , 2021, vol. 16(5):455. doi: 10.15866/iree.v16i5.18132.
8. O. Kupraty. Mathematical modelling of construction of ship turning trajectory using autonomous bow thruster work and research of bow thruster control specifics. Scientific Journal of Gdynia Maritime University, No. 118, June 2021, pp. 7-23. doi: 10.26408/118.01.
9. Andrzej Kopczyński. Hybrid expert system for computer-aided design of ship thruster subsystems. IEEE Access, Volume 8, 2020. doi:10.1109/ACCESS.2020.2982264.
10. Ruth, E. Propulsion Control and Thrust Allocation on Marine Vessels. Ph.D. Thesis, NTNU Norwegian University of Science and Technology, Trondheim, Norway, 2008. 222 p.
11. Jarosław Artyszuk and Paweł Zalewski. Energy Savings by Optimization of Thrusters Allocation during Complex Ship Manoeuvres. Energies 2021, 14(16), 4959; doi:10.3390/en14164959.
12. Яровенко В. А. Расчет и оптимизация переходных режимов пропульсивных комплексов электроходов. Одесса: «Маяк», 1999. 188 с.
13. Небеснов В. И. Вопросы совместной работы двигателей, винтов, и корпуса судна. Судостроение, 1965. 247 с.

14. Яровенко В.А., Черников П.С. Метод расчета переходных режимов гребных электроэнергетических установок электроходов. Електротехніка і електромеханіка, 2017, № 6, С. 32-41. doi: 10.20998/2074-272X.2017.6.05.
15. Яровенко В.А., Зарицкая Е.И. Способ оценки нагрузок на гребные электрические установки электроходов при циркуляционном движении *Вісник* Одеського державного морського університету. – Одеса: ОНМУ. 2014. № 1(40). С. 89-103.

REFERENCES

1. Hansen J. F. (2008). Modeling and Control of Marine power System: Thesis for the Degree of Philosophy Doctor / J. F. Hansen. Norwegian University of Science and Technology. 119 p.
2. Radan D. (2008). Integrated Control of Marine Electrical Power System: Thesis for the Degree of Philosophy Doctor / D. Radan. Norwegian University of Science and Technology. 231 p.
3. Yukun Feng, Zuogang Chen, Yi Dai, Ping Wang. (2020). An experimental and numerical investigation on hydrodynamic characteristics of the bow thruster. Ocean Engineering, vol. 209(8):107348. doi: 10.1016/j.oceaneng.2020.107348.
4. Teresa Abramowicz-Gerigk, Miroslaw K. Gerigk. (2020). Experimental study on the selected aspects of bow thruster generated flow field at ship zero-speed conditions. Ocean Engineering, vol. 209(92):107463. doi: 10.1016/j.oceaneng.2020.107463.
5. Liu Hui, Feng Yukun, Chen Zuogang, Dai Yi, Tian Ximin. (2017). Numerical Study of Pressure Fluctuation for Bow Thruster. Journal of Shanghai Jiaotong University, vol. 51(3), pp.294-299. doi: 10.16183/j.cnki.jsjtu.2017.03.007.
6. Ionut Cristian Scurtu, Valentin Oncica. (2018). Combined CFX and Structural Simulation for Bow Thrusters Loading under Operating Conditions. Journal of Physics Conference Series, vol. 1122(1):012024. doi: 10.1088/1742-6596/1122/1/012024.
7. Sardono Sarwito, Semin Semin, Muhammad Badrus Zaman, Kamarul Hawari Ghazali. (2021). Unbalanced Voltages of Bow Thruster Motor Performance in the Ship Using Simulation. International Review of Electrical Engineering (IREE), vol. 16(5):455. doi: 10.15866/iree.v16i5.18132.
8. O. Kupraty. (2021 June). Mathematical modelling of construction of ship turning trajectory using autonomous bow thruster work and research of bow thruster control specifics. Scientific Journal of Gdynia Maritime University, No. 118, pp. 7-23. doi: 10.26408/118.01.
9. Andrzej Kopczyński. (2020). Hybrid expert system for computer-aided design of ship thruster subsystems. IEEE Access, Volume 8, doi:10.1109/ACCESS.2020.2982264.

10. Ruth, E. (2008). Propulsion Control and Thrust Allocation on Marine Vessels. PhD. Thesis, NTNU Norwegian University of Science and Technology, Trondheim, Norway. 222 p.
11. Jarosław Artyszuk and Paweł Zalewski. (2021). Energy Savings by Optimization of Thrusters Allocation during Complex Ship Manoeuvres. Energies, 14(16), 4959; doi:10.3390/en14164959.
12. Yarovenko V.A. (1999). Calculation and optimization of transient regimes of propulsion complexes of electric vessels. [Raschet i optimizatsiia perekhodnykh rezhimov propul'sivnykh kompleksov elektrokhodov]. Odessa: Mayak Publ. 188 p. [in Ukrainian].
13. Nebesnov V.I. (1965). Questions of the joint operation of engines, propellers, and hull of the vessel [Voprosy sovmestnoi raboty dvigatelei, vintov, i korpusa sudna]. Shipbuilding Publ., 247 p. [in Ukrainian].
14. Yarovenko V.A., Chernikov P.S. (2017). A calculation method of transient modes of electric ships' propelling electric plants. [Metod rascheta perekhodnykh rezhimov grebnykh elektroenergeticheskikh ustanovok elektrokhodov]. Electrical engineering & electromechanics, no. 6, pp. 32-41. doi: 10.20998/2074-272X.2017.6.05. [in Ukrainian].
15. Yarovenko V.A., Zarickaya E.I. (2014). A method for assessing loads on propulsion electric installations of electric ships during circulation motion. [Sposob ocenki nagruzok na grebnye elektricheskie ustanovki elektrohodov pri cirkulyacionnom dvizhenii]. Visnik Odeskogo derzhavnogo morskogo universitetu. Odesa: ONMU. № 1(40). P. 89-103. [in Ukrainian].