Power Plant, Propulsion Complex and Control System of Autonomous Dual-Purpose Underwater Vehicle

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Synopsis

The integrated use of small autonomous underwater vehicles (AUV) - unmanned vehicles with the radius of autonomous action up to 10 km and deadweight up to 500 kg, allows us to solve many practically significant and important problems inherent in the current economic and military-political situation of Ukraine. There is an important task that is part of the "Military doctrine of Ukraine" and "Concept of development of the security and defense sector of Ukraine", namely the production in the Ukraine of modern small-sized AUVs, which are designed to perform specific tasks when in military and civilian use. It is believed that this task is solved either by the purchase of imported AUVs (for civilian use only), or only if there is sufficient funding for certain areas of research and the creation of military AUVs which will require significant resources. A conceptual solution is proposed, which significantly reduces the resources needed to create a dual-purpose (for civil and military use) AUV. This will use a mixture of hardware, including parts of the power plant, propulsion system, energy management system, dynamic positioning system from commercial vehicles and will be modular in its construction. The basis for the construction of individual modules is a comprehensive automation of all functions, computerization, implementation of group technology, providing high flexibility. Functional-technological structure of the automated module consists of two components: functional structure (nomenclature of assembled parts, their properties, complex operations, organization of processes, level of re-installation, etc.) and technological structure (control technology, technological features, hierarchy of components, etc.). Central in modular technological processes is re-installation, which is the basis of their efficiency.

Keywords: autonomous underwater vehicles, control algorithms, power plant, propulsion induction electric motor, frequency converter, formalization of the physical model, computational fluid dynamics

1. Introduction

The complex use of diesels with electronic injection, brushless generators, electric propulsion systems theoretically allow the creation of underwater vehicles with high-precision dynamic stabilization at any geographical position in severe hydrometeorological conditions. This is a prerequisite for AUV systems and is in fact no different to the requirements for underwater weapons. The processes of energy efficient energy transfer in the power plants of AUV with combined propulsion complexes (CPC) are not usually studied [31]. The power plant for underwater vehicles (PPUV), created for specific types of vehicles with Dynamic Positioning (DP) systems, have special requirements for energy consumption and energy efficiency. The multifunctional capabilities of DP vessels can be used only to a limited extent, because their efficient operation requires power that significantly exceeds that of modern PPUVs with no DP systems. The conceptual development of the PPUV of such vessels with DP is important in the creation of specialized CPCs, the use of special types of electric drives, the use of specialized energy sources and controls.

Achieving a balance between high precision dynamic positioning by the vessel whilst maintaining energy efficiency and stability of the PPUV CPC can be problematic. However, there is a contradiction and demand of practice – to achieve maximum energy efficiency while maintaining the objectives of safety, ecology and, most importantly – the implementation of the main technological task of a AUV. Even the preliminary analysis [4, 6, 14, 16, 18] shows that the use of special controls and modified CPCs will lead to at least a 30% increase in the efficiency of power conversion from energy sources to propellers. But this problem is not solved by methods of almost uncontrolled counteraction of the force of the propeller thrust due to the coordinated counterbalance to external perturbation.

The authors analyzed the recommendations for assessing the characteristics of the CPC PPUV: calculating the power of the engines and determining their type, completing the propulsion complexes of various types. These data were obtained on the basis of empirical experience in design and operation, as well as statistical processing of information about underwater vehicles (private joint-stock company "Chernomorsudnoproekt", Ukraine) [19].

Author's Biography
Vitalii Budashko is a Dean of Automation and Electrical Engineering Faculty of the National University "Odessa Maritime Academy", ngineer, he has a background in both Mechanical and Electrical Engineering and has lead Research project funded by the Ministry of Education and Science of Ukraine: "Energy efficient dual purpose vessel positioning system" and "Power plant, propulsive complex and control system of an autonomous dual-purpose floating apparatus"

Analysis of the current state of research, approaches and methodology [23, 26, 27, 30], solving problems of improving the efficiency of vessels with DP, PPUV CPC for various purposes (international concerns Wartsila, Danfoss) do not allow us to confidently declare a solution to the problem of reducing efficiency and increasing failures during normal operation of vessels and in the modes of the DP. The generalization of the results of studies of the performance characteristics of underwater vehicles with CPC and DP system, performed by different authors [4, 23, 26, 27, 31], and their methods do not allow us, with sufficient accuracy sufficient accuracy to perform calculations of running and dynamic qualities of underwater vehicles for different purposes. Model and field tests of propellers, empirical methods for determining the resistance, as well as the calculation and design of engines of various types, cause complex, unresolved issues of interaction of propellers with the hull [14, 16, 23].

An AUV is a free is a free-floating object with six degrees of freedom - three linear movements and three rotations about the spatial axes coordinate systems. All spatial evolutions of AUV in the aquatic environment can be reduced to two main modes of movement – global movement from the initial position to the object and local maneuvering over the object. If in in the first mode, translational and relatively rectilinear movements prevail, in the second there are no preferred movements. In all six coordinates, the AUV moves equally and there is no advantage of any coordinate. The AUV as a free-floating body perceives numerous power disturbances from the environment and operating equipment. Since the vector disturbances are difficult to predict, it is almost impossible to hold position of the AUV with one propeller, even with a perfect DP system. What is needed is a dynamic positioning system that works in synergy with a multi-propellers CPC, without which AUVs become observation cameras with extremely limited mission capabilities.

Hydrometeorological factors and uncertainties related to the area of navigation, season, fuel prices, oil, crew consistency, etc. have the significant impact on the efficiency of DP systems, their PPUV and CPC. Thus [4, 18, 23, 30, 31]:

– the issues of substantiation of the type, determination of the optimal (rational) architecture and main characteristics of the CPC in the implementation of PPUV projects are not given enough attention, and most existing methods of assessing the effectiveness of PPUV are used outside the systematic approach to design and consequently do not always meet modern requirements [4, 18, 31];

– the promising direction in the implementation of work related to improving the efficiency of DP, PPUV and CPC systems is the use of modern simulation environments and CAD/CAM/CAE-systems, which allows us to analyse random factors and dynamics of the environment for the operation of DP systems [18, 19, 26];

– relevant for AUV and dual-use are the issues of increasing the reliability and efficiency of the CPC PPUV with guaranteed performance of technological tasks by the vessel [26, 27, 30];

– insufficiently covered issues related to the automation of work on the design and technological preparation of production in projects to improve the efficiency of the CPC PPUV AUV.

2. Purpose of work

Research has been carried out on the processes of energy processes of energy-saving dynamic positioning, control, conversion and energy transfer in PPUV CPC of AUV-purpose vessels with improvement of systems, hardware and software, development of methods of guaranteed performance of special and basic technological tasks of AUV under the condition of high energy efficiency of functioning of their PPUV of the CPC working in various difficult operational modes.

3. Contents and results of the research

The authors proposed improved methods and algorithms for monitoring and control of the moment of the CPC PPUV (for example, patents of Ukraine №100819 from 10.08.2015, №107006 from 03.06.2016, №108074 from 26.06.2016) and construction the synergistic structure of the control system [7, 8-13, 15, 20, 25], theoretically allow us to solve the problem of optimizing the process of controllability of the DP system while increasing the efficiency of power transmission to the propellers, increasing reliability and expanding functionality, in particular – dual purpose vessels (civilian and military).

Advanced control algorithms [7, 8, 10, 12, 15, 25] allow this to be achieved, based on the application of independent input load characteristics, to generate propeller torques, implement the necessary control signals taking the location of active thrusts relative to the hull, quickly reconfigure environmentally dependent parameters. Using the results of similar of similar research [29], dependences of crossing of typical situations operational parameters were obtained for PPUV CPC [9]:

$$\begin{aligned}&d_i=0;\ a_{ij}=0;\ j=0;\ j=1,2,...,L;\\&\exists k=1,2,...,L;\ p_{is}\in P_{ik},\ s=1,2,...,S\Rightarrow\\&\Rightarrow d_i=1;\ b_{ks}=1;\ a_{ik}=1;\\&\bar{C}_{ik}\cup\bar{C}_{ij},\ j=1,2,...,L;\end{aligned} \quad (1)$$

where: d_i, b_s and a_j – auxiliary indicator variables of the iterative process;

p_{is} – s-th sign of the situational factor;

P_{ik} – the set of characteristic features of the k-th typical situation factor for the i-th operating mode identifier;

$\bar{C}_{ik}$ – set of variables taken into account in the modified task;

$\bar{C}_{ij}$ – an average set of typical situational factors for which $a_{ij} \neq 0$.

Based on the obtained dependences [9, 20], the authors are developing the reduced (1:50) physical model of the multifunctional propulsion configuration with a DP system (Fig. 1), which will help prove the effectiveness of the proposed solutions. At the level of technical implementation, in the links of orientation, stabilization, navigation and control, the authors introduce such elements as solid-wave gyroscopes and piezoelectric transducers, which, in contrast to traditionally used devices in DP systems, can independently measure angles and speed [9-11, 13, 20].

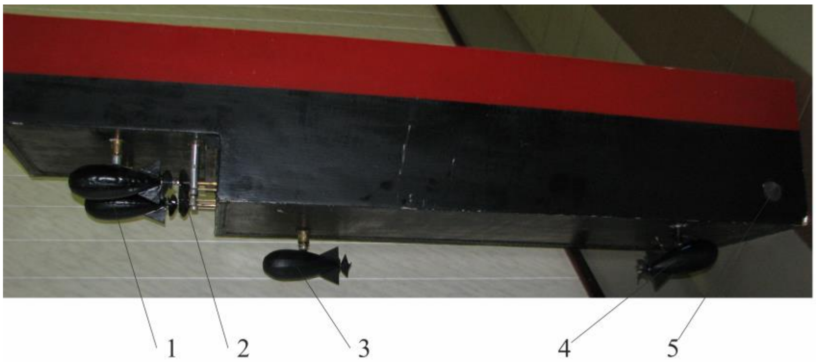

Figure 1: Physical modeling of a multifunctional propulsion complexes; 1 – steering device of the CRP system; 2 – the main electric motor of the CRP system; 3 – aft steering device; 4 – steering device with two degrees of freedom; 5 – tunnel steering device.

The study of the principles of synthesis and operation of DP systems equipped with CPCs reveals the widespread use of typical PID-controllers in different circuits of the control system, despite the significant shortcomings – the complexity of parameterization, noise sensitivity, unreasonable energy consumption and others [1, 3, 5, 17].

There is no open access analysis of AUV. It is known [4, 30] that in some DPS1 systems (according to the classification of the American Bureau of Shipping, ABS) it is possible to "shut down" the main and auxiliary engines, thrusters, and the vessel will keep a position even in difficult weather conditions. Sometimes [14] the operation of underwater vehicles with DP systems (DPS2), where there is a global satellite navigation system (GNSS) with a FanBeam device and a working autopilot, is reduced to the operation of the algorithm DPS1. On state-of-the-art beta versions of K-POS systems (Kongsberg proprietary system) [6, 23, 27], the underwater vehicles will be very difficult to steer in some situations. Increasing the speed of the DP system gives significant technological advantages, but the energy efficiency of such DP systems is very questionable [4, 14, 18].

Assuming that the service requests of the system's DP sensors have a Poisson nature of the flow of requests and the laws of service, then the flow of events in the DP system must have three properties: normal, no effect and stationary, and obey the law of Poisson's propagation [9, 20]:

$$P_n(\tau)=(\lambda\tau)^n\cdot e^{-\lambda\tau}/n!, \quad (2)$$

where: $P_n(\tau)$ – the probability of occurrence of n homogeneous events in the time interval τ;

λ – the constant positive number that defines the average number of events per unit of time.

Thus, the solution of the problem of improving the energy efficiency of AUV with DP: a) providing the necessary, technologically determined, positioning accuracy (for example, to ensure the operation of guidance systems); b) taking into account the action of external disturbances in the open sea, is relevant, has practical significance and is not conceptually resolved.

Improving the accuracy of dynamic positioning systems of special underwater vehicles allows us to use them for AUVs, which can be done through the simultaneous use of energy efficient management methods by: a) construction the special structure of PPUV and CPC, b) using a real-time model in the control loop, c) appropriate corrective actions by means of the forecast analysis of mutual influence of operational parameters of separate elements of PPUV and CPC.

For example, for these DP systems according to formulas (1) and (2), many typical situational factors will have intersections, which affects the adjustment of the corresponding coefficients of PID-regulators, ie [22, 24]:

$$\bar{C}_{ik} \cap \bar{C}_{ij} = \not\in, \ k = 1, 2, ..., L; \quad j=1,2,...,L; \ k \neq j. \tag{3}$$

where: $\bar{C}_i$ – the set of situational factors of the operating mode;
L – the subset $\bar{C}_i$, k = 1, 2, ..., L, relevant to typical situational factors. All current situations are evaluated for belonging to a particular set $\bar{C}_{kj}$, k = 1, 2, ..., L, and the task is replaced by the task equivalent to the typical situation $\bar{C}_{kj}$.

According to the results of research, the following are determined: a) criteria for assessing the quality of power transmission from energy sources to propulsion systems in the CPC PPUV in different operating conditions; b) methods for forecasting excess power consumption during changes in the operational regime of dual-use vessels; c) criteria for assessing the derivation efficiency of CPC engines in order to improve the energy performance of PPUV and to develop a methodology for matching the characteristics of motors of CPC for the projected analysis of power conversion processes in PPUV.

In particular, taking to formulas (1) and (3), for the set of situational factors $\bar{C}_{kj}$ of the operating mode, we define the corresponding intersections for k = 1, 2, ..., L, s = 1, 2, ..., S. Indicator variables of the iterative processes d_i, b_s, and a_j change arbitrarily within the set of characteristic features of the k – the typical situational factor for the i-th identifier of the operational mode P_{ik} (Fig. 2). The set of variables of the modified problem is an intersecting set of typical situational factors for which $a_{ij} \neq 0$.

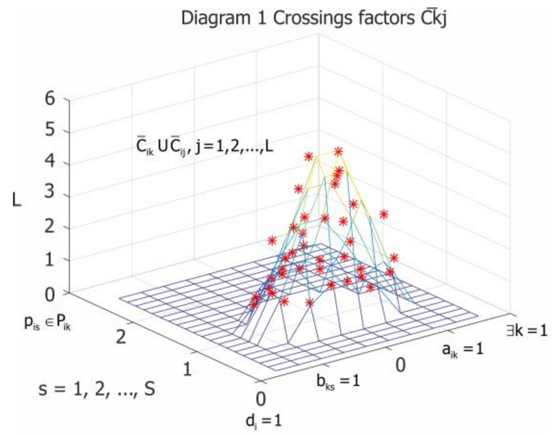

Figure 2: The intersections of the set of situational factors $\bar{C}kj$ of the operational mode for k = 1, 2, ..., L, s = 1, 2, ..., S

From the fig. 2, we can conclude that the determination of the values of the probabilistic coefficients of the disturbing factors applied to dynamic positioning systems and the formation of the configuration matrix of the compensating forces with the determination of the place of application is possible based on the corresponding identification factors. Obtaining correction factors affecting the components of forces and moments proportional to the size of the model and the real object tied to the original geometry is possible by formalizing physical models with the means of identifying disturbing factors on the line of the compensating element.

Mathematical models have been developed: a) power transfer in the CPC PPUV of different types, which will allow us to assess the energy efficiency and quality of processes in the DP of underwater vehicles equipped with different types of electric motors and propulsion and choose the most efficient solution; b) PPUV of the CPC, taking random factors, which are caused, firstly, by changes in the operating modes of PPUV and which directly affect the CPC, and secondly, by changes in the environment that affects the CPC, and indirectly the PPUV. This allows you to justify the type and main characteristics of the PPUV.

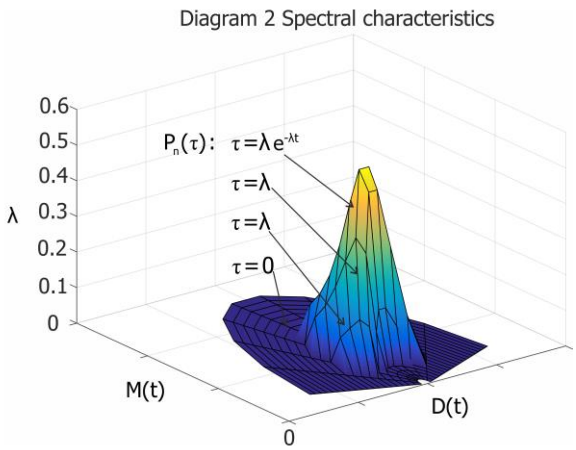

Figure 3: Mathematical expectation of the situational factor that will cause the system to exit from the stable state.

The developed methods are: a) prediction of possible operational reduction of efficiency of functioning of motors of PPUV and motors of CPC of the DP system with allowing for more perfect positioning; b) structural and parametric identification of PPUV and CPC based on the results of operational observations using DMI (Data Mining Index)-models in order to achieve maximum energy efficiency of controls; c) automated design of CPC PPUV, based on the use of modern CAD/CAM/CAE-systems. According to (2) for the DP of the CPC control system, which is under the influence of nondeterministic loads, the distribution of the intensity of applications for perturbations following one another with an interval less than the average value of $1/\lambda$ is shown in Fig. 3 [9, 20]. The increase in the statistics of the frequency of significant identification factors of process characteristics in CPC and PPUV during iterative procedures is proportional to the sample size and does not lead to an increase in variables and coefficients of regression models. Random values of variable perturbing effects are not correlated, which is evidence of the premise of applying the principles of composition of regression models according to the results of experimental studies.

4. Conclusions and recommendations

1. Using a modified direct torque controller such as Direct Torque Control or a vector speed controllers [24] (for example, Vector Oriental Control) and the like, the models of which are presented in [23, 26, 27, 30], do not allow us to correlate the coordinates of the electric drives of the CPC in accordance with the operating mode. Due to the lack of appropriate elements in the structure of these systems, smooth switching of positioning modes is possible. Therefore we can conclude that the results obtained by these authors during their modelling is very unique.

2. Further research is planned to compensate for the reduction and change in direction of thrust of the propellers due to the interaction of the flow from the rudders with the hull, the impact of the propulsion flow from one engine on the neighbouring one, the Coanda effect, for which the authors are developing the physical model of CPC with microcontroller control system [28].

3. The expected results are consistent with the requirements of the International Maritime Classification Organizations to the CPC PPUV of vessels operating for DP modes. The results of the work can be used in the design and construction of main and auxiliary PPUV and control systems of modern autonomous underwater dual-purpose vehicles. The use of the results of the study aims to fully create opportunities for solving problems to achieve improvements in reliability, efficiency, security of the CPC PPUV, and the implementation of special tasks for the world fleet [2, 18].

4. The social and economic effect of the implementation of the survey results will exceed the costs, as the expected results are aimed at solving the main problems of Ukraine – providing the state with energy resources and improving its defense capabilities.

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