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DEVELOPMENT OF SPECIALIZED MODELING COMPLEX TO STUDY CONTROL SYSTEMS OF MOVABLE MARITIME OBJECTS

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Розроблено, створено, випробувано і впроваджено у навчальному процесі спеціалізований моделюючий комплекс для дослідження ефективності систем керування електроприводами постійного та змінного струму, до складу якого входить метрологічно атестований навчально-дослідницький лабораторний засіб «Стенд випробувальний СВ-1». Показано можливість синтезу систем керування рушійним пристроєм підводного апарата з різними типами регуляторів і їх подальшою корекцією

Ключові слова: регулятор, рушійний пристрій, підводний апарат, спеціалізований моделюючий комплекс, точність керування

Разработан, создан, испытан и внедрен в учебный процесс специализированный моделирующий комплекс для исследования эффективности систем управления электроприводами постоянного и переменного тока, в состав которого входит метрологически аттестованное учебно-исследовательское лабораторное средство «Стенд испытательный СВ-1». Показана возможность синтеза систем управления движительным устройством подводного аппарата с различными типами регуляторов и их последующей коррекцией

Ключевые слова: движительное устройство, регулятор, подводный аппарат, специализированный моделирующий комплекс, точность управления

1. Introduction

Contemporary movable maritime objects (MMO) are a large class of dynamical systems that function under conditions of considerable impact from the environment [1, 2]. MMO include the most common water tonnage vessels, vessels with the dynamic principle of support (hovercrafts, hydrofoils), submersibles-robots, search and exploration systems and others.

Movable maritime objects are able to solve efficiently a number of important tasks for different purposes, the volume of which is constantly increased. In this regard, there are constantly evolving requirements for maneuverability, functionality of MMO, productivity of operations performed, which implies improving motion control systems for the objects of marine robotics. Such systems should provide for accurate stabilization, dynamic positioning and its orientation in a geographical point of the water space.

Development of control systems (CS) over movable objects with different purposes and the methods of their modeling have always been in the focus of leading scientists [3–5].

However, despite significant achievements in the design and research into motion control systems of ships and submersibles, one of the important problems associated with the design and operation of objects in marine robotics is the task of creating high-quality control systems, which should provide for desired dynamics and precision when working out program trajectories in motion.

2. Literature review and problem statement

Large-scale scientific research, military, search-and-rescue operations, resolving actual problems on ecological safety and environmental protection in water space, conducting anti-terrorist measures resulted in the growing need for such a class of MMO as underwater vehicles (UV) [6, 7].

It is known that one of the UV controlling mechanisms, responsible for its motion control and precision of spatial position, is the propulsion-steering complex (PSC), which includes propulsion devices (PD) [8]. However, it is the UV PSC that has remained insufficiently examined up to now as a control object.

The difficulties arise in the course of developing control systems for propulsion device of underwater vehicle that are largely associated with the uncertainty in information on the state of parameters of individual nodes and units, UV deviation from the assigned motion trajectory, and are caused by the existence of permanently occurring perturbations from the external environment [9].

Existing methods for the synthesis of nonlinear, self-adjusting and adaptive systems [10] require costly control systems due to the large dimensionality and multiple connectedness of control object, which require non-stop identification of control object's parameters and sophisticated tuning of regulators [11].

There is a known approach according to which UV PD control, as a rule, is based on the identification of inconsistency between estimations and the assigned values of motion parameters in the coordinate system, associated with underwater vehicle, and subsequent application of the proportional-integral-differential (PID) regulator [12]. This approach made it possible to create motion control systems for complicated curved trajectories by dividing the curvilinear trajectory of motion into rectilinear sections, transition to each of which requires redefining the coefficients of PID regulator [13].

An important consideration in the design of UV PD control systems is that UVs cover considerable distances under water with small deviations from the assigned motion trajectory, that is, linear motion is the basic type of underwater vehicle motion. That is why requirements regarding the improvement in accuracy through automation address in particular this type of motion.

Resolving this task is to a large degree related to the changes in hydrodynamic parameters of UV modules, which requires developing new, and improving those existing, PSC designs, which include propulsion devices with barounloaded induction motors (BIM), filled with liquid dielectric [14]. A simple design of BIM and low cost contribute to extending their standard type and dimension series and mass production.

In modern designing practice, computer experiment is an effective innovative means for the synthesis of complex movable objects CS [15]. This applies, first of all, to solving the problems, which are hard to formalize, as well as to the cases when measurement data are insufficiently complete and obtained under conditions of existing uncertainties of structural, statistical and parametric nature. Therefore, there is a need to devise modeling complexes [16], which would make it possible to do without using expensive equipment and special pools, as well as to provide for the safety of conducted experiments.

There are such known complexes as Webots [17] that allows the visualization of results of simulation in a three-dimensional space and realizes the principle of rapid prototyping; the RobotSim environment [18] that provides for the simulation of movable robots motion with taking into account effects of their interaction with the environment; the Microsoft Robotic Studio programming complex [19] that enables devising the algorithms to control the motion of mobile robots with different purposes, etc.

However, despite all essential capacities of the aforementioned simulating complexes, there are problems, for example, on the verification of correctness in the control algorithms implementation by a real CS at its work under different modes, when their application is either impossible or requires significant modifications. This necessitates creating specialized modeling complexes for the semi-natural simulation of control systems that operate PD with BIM, which, through the automated tuning of parameters for regulators and programming signals, provide for the highly accurate horizontal linear motion of the underwater vehicle.

3. The aim and tasks of the study

The aim of present research is to develop, create and test a specialized modeling complex for assessing performance effectiveness of control systems for propulsion device of the underwater vehicle.

To accomplish the set aim, the following tasks were to be solved:

– to design program and electromechanical parts of specialized modeling complex (SMC), intended to study performance effectiveness of CS for electric drives with direct and alternating current;

– to conduct metrological attestation of training and research laboratory set-up “Testing Stand SV-1”, which is a part of SMC;

– to implement and test by SMC a CS of PD with BIM at horizontal rectilinear UV motion with the synthesized regulators.

4. Materials and methods of examining performance effectiveness of control systems for propulsion device of underwater vehicle at a specialized modeling complex

4. 1. Development of specialized modeling complex

At present, a considerable part of the research into electric drive CS is conducted by mathematical modeling using the MATLAB, MathCAD programming packages [20]. It is known that, in this case, the assumptions made when describing CS blocks lead to a decrease in its accuracy, stability, etc. [21, 22]. To minimize the impact of assumptions on the quality control of the system, it is necessary to perform experiments on a particular electric drive, which is not always possible, or on its full-scale imitation model.

For this purpose, we developed a specialized modeling complex consisting of specialized software and training-research laboratory set-up “Testing Stand SV-1”. The latter is designed to study performance effectiveness of CS for electric drives of direct or alternating current in the propulsion-steering complexes of underwater vehicles.

“Testing Stand SV-1” consists of the following units:

– electromechanical unit, which includes electric machines for testing and loading;

– power unit 1, intended to power machines for testing. One can use a source with adjustable frequency and power voltage for induction or synchronous motors or the source of regulated constant voltage for direct current machines;

– power unit 2 that includes the source of regulated constant voltage to power the load machine;

– measuring unit with sensors of velocity, position angle, current, voltage, temperature;

– connecting unit, intended to connect the measuring unit, power units 1 and 2 with PC;

– control unit, which includes a PC.

A schematic of Testing Stand SV-1 is shown in Fig. 1.

Allocation into channels for a tested machine and the load machine is due to the unification in modules, and to reduce influence of one machine to another.

Specialized peripheral module (SPM), in turn, includes a connecting unit to PC, control unit, power unit (PU), measuring unit.

SPM allows us to enter feedback signals into personal computer and to receive a control signal. The basic element of SPM is the microcontroller Microchip PIC18F2431(DD1) (USA). The choice of microcontroller is predetermined by the availability of high-performance ADC (analog-to-digital converter) and PW (pulse width) hardware modulator with advanced features.

RC-filters are installed before the analog inputs and are intended only for the suppression of high-frequency interference, the main filtering is realized by the microcontroller’s software. From the outputs of hardware PW-modulator, signals are fed to the driver IR2133(DD2), which controls power transistors and provides for the protection against short circuits and voltage reduction in the control circuit power supply. The output power cascade is the pulse regulator of reducing type (chopper circuit) in which the reverse diode, to enhance efficiency, is replaced with a field-effect transistor. We selected IRFP4710 as the power transistors, which are distinguished by very low channel resistance in the open state – 0.014 Ohm.

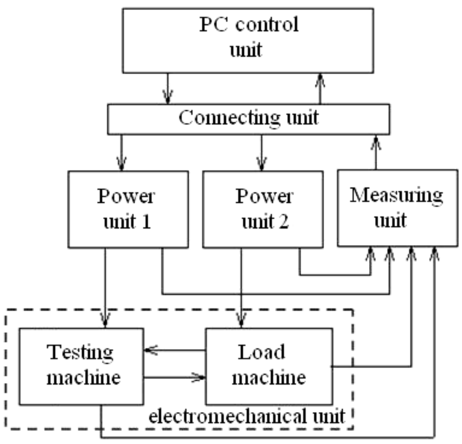


Fig. 1. Schematic of Testing Stand SV-1

At the output of power cascade there is the filter L1C29R29, the purpose of which is limiting the rate of growth in output voltage to protect the insulation of loading and suppress parasitic oscillations in a long line. Connection with PC is realized through the parallel interface. To ensure reliability and electrical safety, the driver (DD3) is galvanically isolated from the main circuit using high-speed optocouplers DA1 and DA2 6N136, driver is powered by the DC/DC-converter DCP010505. PU is powered by the two stabilized sources of 15 and 5 V. Since the 5 V power source is used as the reference for ADC, it is designed as the precision one based on the stabilizer LM317 and the reference voltage source TL431.

The software of the microcontroller is relatively simple. It includes the initialization of peripheral modules in the microcontroller: USART, ADC, PW-modulator and some others [23]. A connecting procedure is periodically triggered that sends measured and filtered feedback signals to the personal computer, receives managing byte and accepts it into the register to manage modulator's duty cycle. Data are transmitted in binary format, the start byte is 00.

Before sending data to a personal computer, it is necessary to convert the measured instantaneous values of feedback signals into the mean ones or into those valid over a period or several periods. Digital filter subroutine is realized in two variants.

The first variant is the IIR filter of second order. We selected the filter with critical attenuation. The choice is due to several reasons: a filter can be implemented using the integer arithmetic; such filter possesses high quality of transient response. For the ease of calculations, it was decided to realize this filter as two links of first order, connected sequentially. Each link is implemented by expression:

$$y_i = \frac{(K-1)y_{i-1} + x_i}{K},$$

where K is the constant coefficient.

If we take $K=2^n$, for example 256, and convert original expression to the form:

$$y_i = \frac{Ky_{i-1} - y_{i-1} + x_i}{K},$$

then, in the course of program implementation, we can do only with integer addition, subtraction and shift. In the MathCAD environment, we modeled such algorithm. Transient response of the filter at sampling frequency 10 kHz is shown in Fig. 2.

$$i := 0..2000; \quad u_{1i} := 256\left|\sin\left(\frac{6\cdot i}{200}\right)\right|;$$

$$u_{2i+1} := \frac{255u_{2i} + u_{1i}}{256}; \quad u_{3i+1} := \frac{255u_{3i} + u_{2i}}{256}.$$

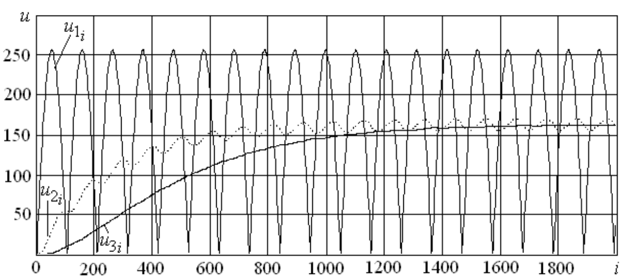


Fig. 2. Transient response of the filter at sampling frequency 10 kHz: curve u_{1i} — examined signal; curve u_{2i} — signal after the first order filter; curve u_{3i} — resultant signal after the second order filter

To enhance high-speed performance of the system, we developed the second variant of the filter – FIR-filter "rolling average". To enable such filter to effectively calculate the mean value over a period at the unstable signal frequency signal, a certain modernization of the traditional algorithm is needed. Such a modernized algorithm is called a "rolling average" synchronous filter. A diagram of the algorithm is shown in Fig. 3.

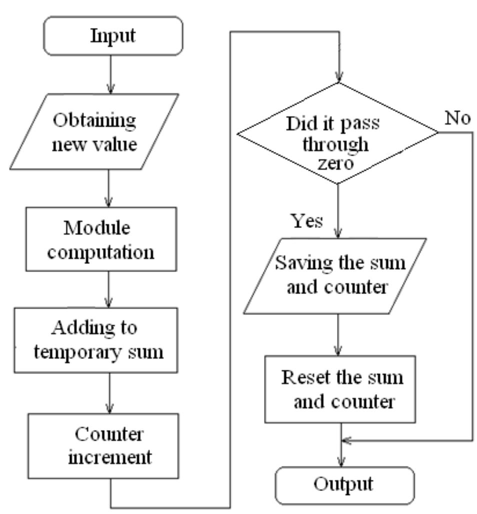


Fig. 3. Diagram of algorithm for the "rolling average" synchronous filter

In the main program, we divide the accumulated amount into the number of taken measurements (counter). Since the microcontroller is not equipped with the operation of dividing realized in hardware, we use a special subroutine for dividing whose feature is the replacement of dividing with multiplying by the number converted into additional code.

A general view of the electromechanical part of Testing Stand SV-1 is shown in Fig. 4.

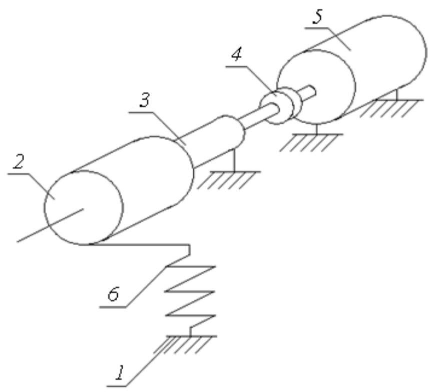


Fig. 4. General view of the electromechanical part of Testing Stand SV–1: 1 – substruction; 2 – stator; 3 – fixed transitional support; 4 – elastic coupling; 5 – testing machine; 6 – elastic element of electronic scales

To ensure controlled load, we use induction motor with a squirrel-cage rotor (loading machine), turned on under the mode of dynamic braking. A peculiarity of the loading machine is that the rotor and stator can rotate independent of each other. This is provided by fixed transition support 3, on which stator 2 is mounted via a spigot on rolling bearings. The rotor has a longer shaft that rotates on rolling bearings fixed in the immobile support. Native bearings were removed from the motor, which allowed us to disconnect the rotor and stator mechanically.

When torque occurs on the motor's shaft, elastic element of electronic scales 6, fixed at one end on substruction 1, and the other on stator, creates a resistance moment and tries to return the stator in the starting position. The rotor is set into rotation through elastic spigot 4 by testing machine 5. When constant voltage is fed to the stator windings, electromagnetic torque is created in them, which tries to turn the stator in the direction opposite to the rotation of rotor until the effort of elastic element 6, applied to the body of the stator, balances electromagnetic torque. Rotation frequency sensor is installed on the spigot from the side of loading machine.

4. 2. Design of rotation frequency measuring sensor for Testing Stand SV-1

Rotation frequency measuring sensor is intended for use on Testing Stand SV-1 as a source of feedback signal in the structure of controlling and measuring systems.

Basic technical specifications:

Maximum rotation speed – 2000 rpm.

Minimum rotation speed – 100 rpm.

Power voltage – 5V.

Sampling frequency – 100 Hz.

Digit capacity – 10 bits.

Range of analog output signal – 0...5 V.

Type of digital output signal – parallel.

Information on the rotation frequency may be obtained by different methods, for example, by using tachogenerators, induction sensors, and discrete sensors. The application of discrete sensors makes it possible to convert information easily into digital code, eliminate errors of linearity and sensitivity, characteristic for analog sensors. When using discrete sensors, there are two conversion methods: to count the pulses over an assigned interval or to measure a time interval between adjacent pulses and compute inverse function. The first method is easier to implement but it requires a long time for measurement. In the case when it is necessary to receive results of measurements over short intervals of time, one should use the second method, although it requires faster performance of measurement circuit.

We selected an incremental encoder as sensor that contains a disk with 60 openings and a special dual optocouple with optical channel HOA 0901. At rotation frequency 2000 rev/min, we shall receive the frequency of change in the openings of the sensor of 2 kHz. To provide for resolution of 10 bits, we need calculation pulse frequency of not less than 2.048 MHz. The microcontrollers with traditional clock frequency of 20 MHz, in the case of software implementation, cannot achieve the calculation pulse frequency of 2.048 MHz, which is why we chose microcontroller with hardware interface of quadrature encoder PIC18F2431. The specified interface allows measuring the passing period of input pulses by hardware, controlling the direction of rotation. We shall select the frequency rate of calculated pulses at 5 MHz.

We selected the mode of feedback module – interface of quadrature encoder, the mode for measuring speed – enabled, update mode is fourfold, index signal – not applied, dividing coefficient of speed measurement circuit is 4. In this setting, we have one event in measuring speed per one period of the encoder. To enhance the noise immunity, we enabled internal filter whose operation principle is as follows: change on the signal will be processed if the signal level is stable for some time (in this case, 32 cycles). The sequence of commands to initialize the interface will be as follows:

```
movlw     b'00011001';1:4, 4 update
movwf     QEICON
bsf       CAP1CON, CAP1REN
movlw     b'00111100'
movwf     DFLTCON
```

Given the fact that the frequency of calculated pulses is 5 MHz, the rotation frequency of mechanism (in RPM) will be equal to $5000000/N_x$, where N_x is the result of measurement. If number N_x is represented in the form of a double-byte integer, then the minimal measured rotation frequency will amount to 76 rpm, which corresponds to the task with a small margin.

The principal electrical scheme of rotation frequency measuring sensor is shown in Fig. 5.

In addition to the microcontroller, the device contains a digital-to-analog converter MCP4921 for the output of signal in analog form and port extender MC74HC595A for the output of signals in digital form. All elements of the device are connected by the synchronous serial interface SPI.

Diagram of algorithm for the rotation frequency measuring sensor operation is shown in Fig. 6. In the beginning of each cycle of the algorithm, unit 1 checks if the time interval that corresponds to the sampling frequency is completed. If the interval is completed, then we shall proceed to unit 2 where it is checked if speed measurement events occurred during this time interval. If the events are missing, then we shall consider rotation speed to be below the minimal measured one and it can be considered equal to zero.

In unit 3, the speed is reset. Then the resulting value is derived. In unit 4, analog signal is sent through DAC (digital-to-analog converter); in unit 6, digital signal is sent through the port extender. If, when checking in unit 2 it was revealed that the speed measurement events did occur, then we shall proceed to unit 6, which computes the mean value of duration of period N_x, because at high rotation frequencies, there may occur more than one speed measurement event over the sampling period. Next, unit 7 calculates rotation frequency in revolutions per minute.

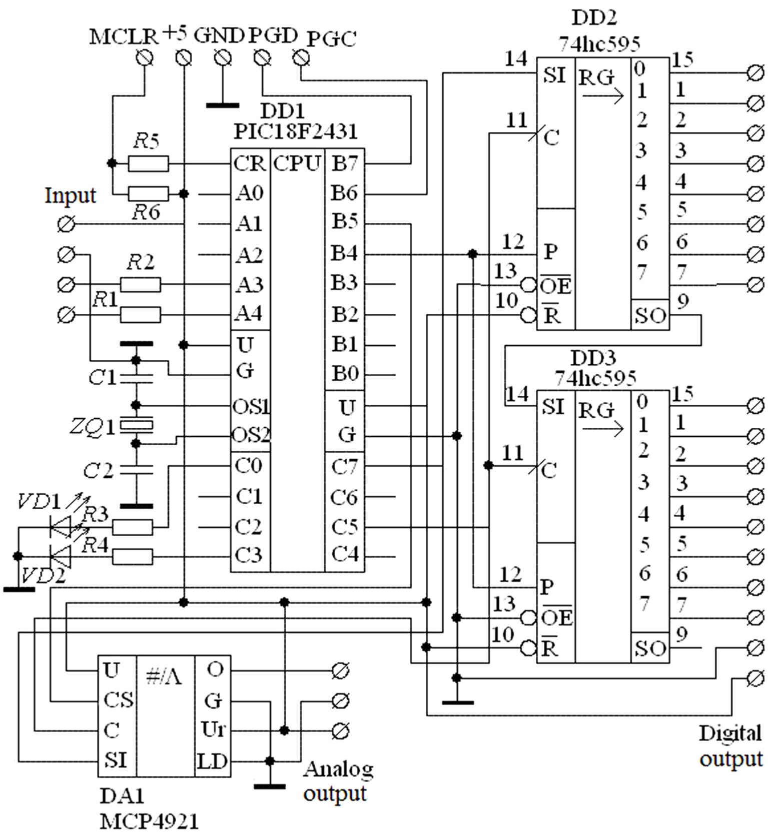


Fig. 5. Principal electrical scheme of rotation frequency measuring sensor

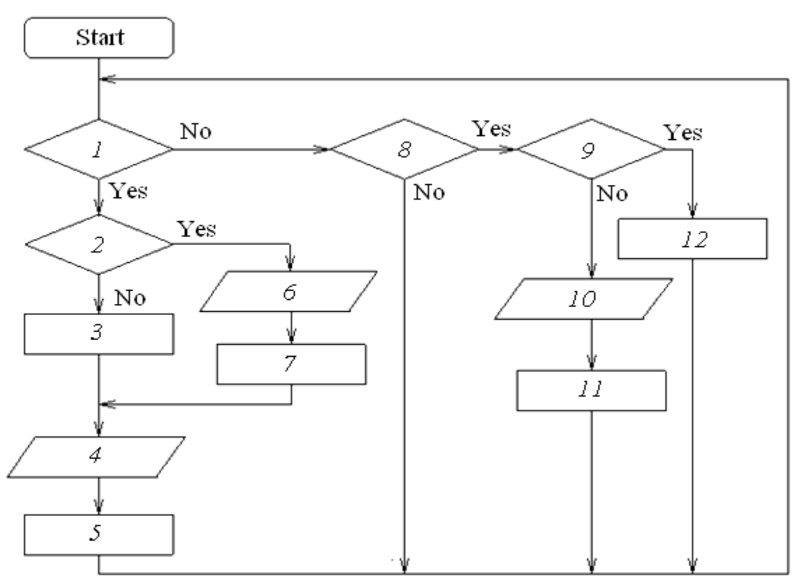


Fig. 6. Diagram of algorithm for the rotation frequency measuring sensor operation

If in unit 1 it was revealed that the time interval is not completed, then we shall proceed to unit 8 – checking the event of speed measurement. If the event did occur, then unit 9 checks timer 5 overflow, which shows that the rotation frequency is too low and goes beyond the measured range. If the overflow did not happen, then unit 10 accumulates the measured magnitude, and in unit 11 we increase the measurement counter. Results of performance of units 10 and 11 are applied in unit 6 to calculate the mean value. In unit 12, the timer is reset. The algorithm runs in cycles, thus the device operates as long as power supply lasts.

To confirm reliability of results of the studies conducted, we performed metrological attestation of the designed training-research laboratory set-up Testing Stand SV-1, intended for examining performance effectiveness of CS for electric drives of different current in the propulsion-steering complexes of underwater vehicles.

4. 3. Experimental study by SMC of the control systems for PD with BIM at horizontal rectilinear motion of UV with different regulators

For experimental studies by SMC of SC for PD at horizontal rectilinear motion of UV, we devised Simulink-models of CS for PD to stabilize angular velocity, stop the propeller (PR) and speed of UV movement at its horizontal rectilinear motion with the synthesized in [24] adaptive PID controllers and fuzzy logic controllers (Fig. 7).

Simulink-models (Fig. 7) consist of the following units:

– unit “voltageout” is used for converting and transferring control action to the drive of controlling machine;

– unit “torque” is intended for converting and transferring control action to the drive of loading machine;

– unit “speedin” serves for receiving and converting signals from the rotation frequency sensor of controlling machine;

– unit “temp” is intended for receiving and converting signal from the working machine’s liquid temperature sensor;

– unit “w” is used to visualize results of the experiment;

– unit “PID” is an adaptive PID regulator;

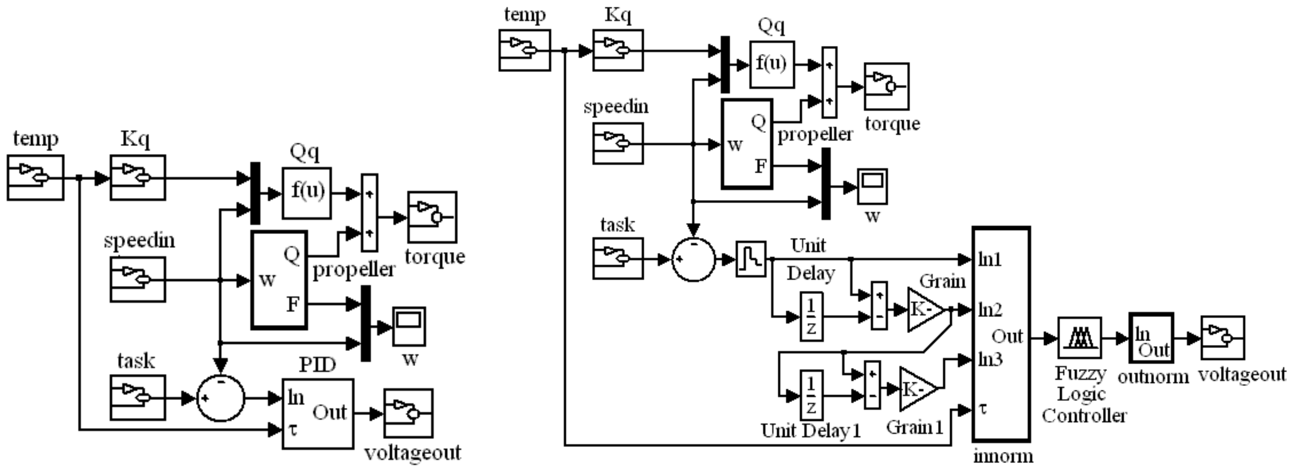
– unit “propeller” is used for the calculation of propeller’s braking torque;

– unit “task” of the Simulink-model functions as the assigning signal for the system (UV propeller’s angular speed);

– unit “innorm” performs fuzzification of error, of first and second derivatives of the error, of the working fluid temperature;

– unit “Fuzzy Logic Controller” carries out calculation of control action;

– unit “outnorm” conducts defuzzification of control action.



a *b*

Fig. 7. Simulink-model for experimental study of CS for PD with BIM of the stabilization of angular velocity of the UV propeller by SMC: *a* — with adaptive PID regulator; *b* — with fuzzy controller

5. Results of studying control systems for PD with BIM at horizontal rectilinear UV motion with different regulators by SMC

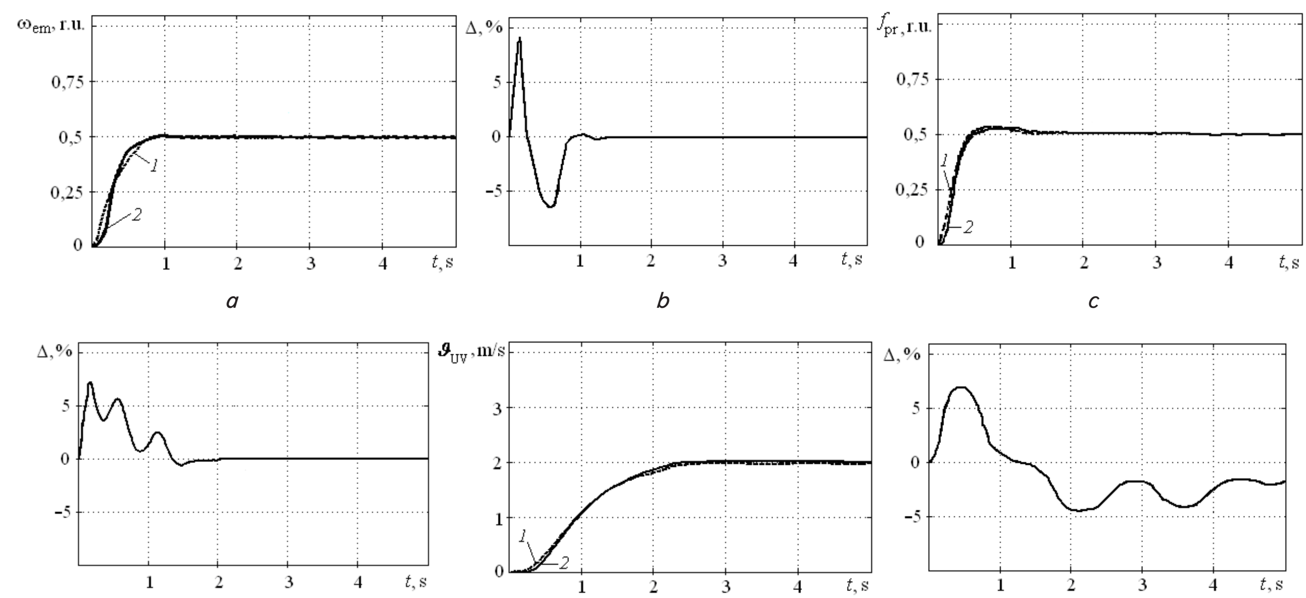
Fig. 8 shows graphs of CS operation for PD with BIM at horizontal rectilinear UV motion with different types of regulators, obtained by computer simulation, and experimental research with the help of SMC.

Legend in Fig. 8:

– curve 1 – results of computer simulation of the work of CS for PD with BIM at the stabilization of PR angular velocity ω_{em} (with adaptive PID-regulator), PR braking f_{pr} (with fuzzy controller) and the moving speed at UV horizontal motion ϑ_{UV} (with fuzzy controller);

– curve 2 – experimental study by SMC of the work of SC for PD with BIM at the stabilization of PR angular velocity ω_{em} (with adaptive PID-regulator), PR braking f_{pr} (with fuzzy controller) and the moving speed at UV horizontal motion ϑ_{UV} (with fuzzy controller).

Graphs in Fig. 8 show that the discrepancy between the results of computer simulation and results of experimental research into the work of CS for PD with BIM at horizontal rectilinear UV motion does not exceed 8 %.



d *e* *f*

Fig. 8. Graphs of CS operation for PD with BIM at horizontal rectilinear UV motion with different types of regulators: *a, c, e* — results of comparison of experimental research into the work of SC for PD with BIM at horizontal rectilinear UV motion with different types of regulators; *b, d, f* — discrepancy between the results of computer simulation and results of experimental research

6. Discussion of results of the SMC development and the study by it of CS for PD with BIM at UV horizontal rectilinear motion with different regulators

A specialized modeling complex that we devised includes in its design:

– electromechanical part in the form of a set of electric motors of alternating and direct current with software-controlled electromechanical load on their working shafts;

– software part that includes the models, developed in the Matlab Simulink programming environment, of CS for PD with BIM at UV horizontal rectilinear motion, data library with regulators of various types;

– interface of electromechanical and software parts.

To confirm reliability of results of the research conducted, we carried out metrological attestation of the devised training-research laboratory set-up Testing Stand SV-1.

Basic characteristics and capabilities of the training-research laboratory set-up Testing Stand SV-1 are represented, in particular:

1. The use of detachable elastic coupling makes it possible in a short time to replace one testing machine with another.

2. Range of capacities of electric machines for testing is from 0.25 to 1.0 kW, rotation speed is up to 2000 rpm.

3. Arrangement by units enables, when using various power equipment (powered by alternating or direct current), creating full-scale models of existing and designed electric drive, working out control systems nodes and developing electric drive SAC as a whole.

4. Availability of PC allows, with minimal time cost, synthesis of a wide range of control algorithms for electric drives and test their performance effectiveness on real electromechanical equipment.

5. In the course of operation, rotation frequency of testing machine is determined and processed by PC. Range of rotation frequency measurement is from 100 to 2000 rpm with a relative error not exceeding ±2 %.

We conducted the following experiments: computer simulation by means of visual programming application Simulink, production semi-field tests by means of the specialized modeling complex and the industrial full-scale – basin tests. The tests demonstrated convergence of results within 8–15 %, caused by taking into account the internal and external components of the processes when modeling the work of propulsion device.

7. Conclusions

1. We developed a program part of the specialized modeling complex, which is a package of applied programs of computer and natural simulation for working out under laboratory conditions of algorithms and principles of control, measurement of energy and dynamic characteristics of electric drives. We designed training-research set-up "Testing Stand SV-1", which is an electromechanical part of the specialized modeling complex.

2. Metrological attestation of training-research set-up "Testing Stand SV-1" was carried out, which makes it possible to provide for the accuracy of research conducted in line with its technical specifications.

3. We demonstrated the possibility of synthesis of CS for PD with BIM at horizontal rectilinear motion of UV with different types of regulators and their subsequent correction by means of the specialized modeling complex. A feasibility of the synthesized CS for PD with BIM at horizontal rectilinear motion of UV was proven experimentally.

The discrepancy between results of computer simulation and the results of experimental research is insignificant and reaches 5–8 %. It was revealed that the existing delay of 0.1...0.15 s in the output signal, which is associated with the peculiarities of processing the input magnitudes (tachometer signal), does not affect the appearance of characteristics of output magnitudes.

The results obtained were implemented into teaching process in the preparation of bachelors and masters at the National University of Shipbuilding named after Admiral Makarov (Ukraine), in the design of control systems for underwater movable objects within the framework of actual scientific research, military tasks, as well as rescue operations on ecological safety and environmental protection in the water space for a number of organizations, including Ministry of Defense of Ukraine, State Service of Ukraine for emergencies and National Academy of Sciences in Ukraine.

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