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Computer simulation of the microprocessor liquid level automatic control system

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ABSTRACT

Today, automation occupies a leading place in most branches of modern society, in almost all types of industry and economy. One of the main tasks of designing modern automatic control systems is the realization of high indicators in terms of accuracy, control range, and speed, taking into account the features of the control object itself. The purpose of the work – researching the microprocessor system of automatic control of the liquid level by means of computer modeling, taking into account the transport delay, the nonlinearity of the control characteristic of the pump and the presence of an insensitivity zone. To achieve the goal, the following tasks were solved: a computer model of a closed microprocessor system for automatic control of the liquid level was developed, taking into account the nonlinearity of the characteristics of the pumping unit and transport delay; a number of experiments were conducted to find the values of PI-regulator coefficients that bring the transient process of a real system with a transport delay as close as possible to the transient process of a system in which there is no transport delay; search for optimal values of the coefficients of the PI controller by minimizing the functional of the root mean square deviation of the real from the specified transient processes. As a result of research, it was established that the minimum points of the functional for the control signal and the liquid level do not coincide. At the same time, at the minimum point of the functional for the liquid level, a larger amplitude of oscillations of the control signal is observed, and at the minimum point of the functional for the control signal – an increase in the duration of the transient process. Therefore, the final decision should be based on the selection of priorities or optimal ratios between the speed and wear of the equipment, which is due to the instability of the control signal.

Keywords: Automatic control system; liquid level; microprocessor; computer simulation; pi controller; optimization.

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INTRODUCTION, FORMULATION OF THE PROBLEM

The modern development of industry is characterized by the desire to improve the technical and technological characteristics of equipment and automated systems with the aim of increasing their quality indicators, reducing production and maintenance costs. In many branches of industry, such as the production of building materials, the food industry, chemical and oil refining production, and others, maintaining a given level of liquid is a widespread and important task, since on the one hand the level set in accordance with the regulations ensures the stability of the technological process, and on the other hand, going beyond the limits permissible values may be the cause of loss of raw material, reduction of productivity, and as a result of economic losses.

It is known that control of the liquid level is necessary to ensure certain technological standards. If the liquid level deviates from the specified parameter, the equipment will not work correctly or the technological process will be suspended. Regulating the level in the reservoir is a common task in water supply and drainage systems. For example, these can be storage tanks at pumping stations, water towers, reception tanks of pumping sewage stations, etc. Water can be supplied to the tank by gravity or by a regulated or non-regulated pump. Tank emptying can also be carried out by gravity or with the help of pumps. The task of management is to maintain the liquid level in the tank at a certain level, which is determined by both technological requirements and economic factors. Maintenance of the specified liquid level is possible only in the case of the same flow of liquid at the inlet and outlet of the tank. At the same time, the flow of liquid is uneven, which is which is due to natural or technological factors. Therefore, a change in fluid flow from a reservoir is often considered a system disturbance. In these conditions, to maintain a constant level of liquid in the tank, it is necessary to adjust the performance of the feed pump accordingly. This task should be performed by the automatic fluid level control system.

Therefore, researchment of the microprocessor system of automatic control of the liquid level by means of computer modeling, taking into account the transport delay, the nonlinearity of the control characteristic of the pump and the presence of an insensitivity zone is an urgent task of scientific interest and practical significance.

1. LITERATURE REVIEW

Controlling the level of liquid in a tank or a certain capacity is a common industrial problem, which is solved in different ways using scientific principles.

Finding the necessary control mode and the way to adjust the regulator is one of the most common tasks on the way to solving this problem [1]. Theoretically, control of the level of liquid in the tank is not particularly difficult; generally known methods of analysis of the quality indicators of the control system are used [2-3]. Taking into account the different properties of control objects, scientists have proposed a number of types of regulators, each of which has certain advantages and disadvantages for each control object.

To set the necessary control stability and speed, PID controllers are often used, which are quite convenient to model in Simulink/Matlab [4, 5], but they also have certain disadvantages when controlling non-linear objects, which is the reason for looking for other approaches to control, one of which is the use of fuzzy logic and fuzzy controllers [5], [6], [7]. When studying different models of liquid containers, it is necessary to take into account various parameters: the shape of the container (cylindrical, conical); a single tank or tanks connected to each other; thermal processes; mixing the contents of the container. For the synthesis of an automatic control system that takes into account the individual features of a specific design, it is recommended to identify the control object [8], [9], [10], thereby obtaining an approximate characteristic.

When using the mathematical description of the control object, the possibilities of using virtual laboratories [11, 12], virtual designers [13, 14] for the development and research of automatic control systems thanks to these objects [15] are expanded.

During the pumping of contaminated liquids and suspensions to a height with the pump turned off, the pipeline is emptied. Installation of a non-return valve is impossible due to the need for constant movement of the suspension. In a stationary state, the suspension is divided into liquid and solid parts, which lead to clogging of the pipeline. As a result of the lack of material in the pipeline at the beginning of the pumping process, a transport delay occurs, which determines the need to reduce the speed of the control system in order to avoid self-oscillating modes.

Taking into account these features of the study of the microprocessor system of automatic control of the liquid level, namely the search for optimal coefficients of the PI controller, which provide the desired characteristics of transient processes, determine the relevance of the work.

2. THE PURPOSE AND TASKS OF THE RESEARCH

The purpose of the work – researching the microprocessor system of automatic control of the liquid level by means of computer modeling, taking into account the transport delay, the nonlinearity of the control characteristic of the pump and the presence of an insensitivity zone.

To achieve the goal, the following tasks were solved: a mathematical and computer model of a closed microprocessor system for automatic control of the liquid level was developed, taking into account the nonlinearity of the characteristics of the pumping unit and transport delay; a number of experiments were conducted to find the values of PI-regulator coefficients that bring the transient process of a real system with a transport delay as close as possible to the transient process of a system in which there is no transport delay; search for optimal values of the coefficients of the PI controller by minimizing the functional of the root mean square deviation of the real from the specified transient processes.

3. DESCRIPTION OF THE LABORATORY STAND

To study the features of start-up and nonlinearity of the pump set, a laboratory stand was developed, which consists of a microprocessor controller MIK-127 [16], two tanks (TANK1 and TANK2), a car windshield washer pump with a DC motor with a nominal supply voltage of 12 V, gain control signal (G), manual control unit (MCU) and level sensor (LS). The block diagram of the laboratory stand is shown in Fig. 1.

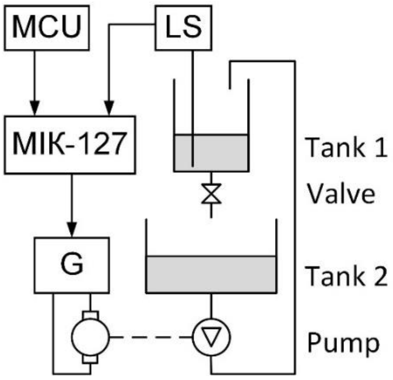


Fig. 1. **The block diagram of a laboratory stand for study automatic liquid level control system**
Source: **compiled by the authors**

Tank 1 is a transparent pipe with a length of 110 cm and an inner diameter of 2.5 cm. The liquid level is measured by the hydrostatic method using the sensor MPX2010DP [17], which is a converter of differential pressure from 0 to 10 kPa into an electrical signal of 0-25 mV at a supply voltage of 10V. The appearance of the stand is presented in Fig.2. The MIK-127 microprocessor controller can be programmed using the keys on the front panel or through the interface using special software - the ALFA visual program editor.

A program has been developed to study the object of the automatic liquid level control system in the ALFA software, which allows setting the control signal on the analog output using the manual task block. The signal from the level sensor is transmitted to the analog input, which is connected to the analog output in the program ALFA. This output is used to record changes in liquid level using an oscilloscope. The current values of the signals are displayed on the front panel of the regulator [8], [18], [19].

Therefore, the developed hardware and software parts of the stand can be used for further research into microprocessor-based liquid level control systems.

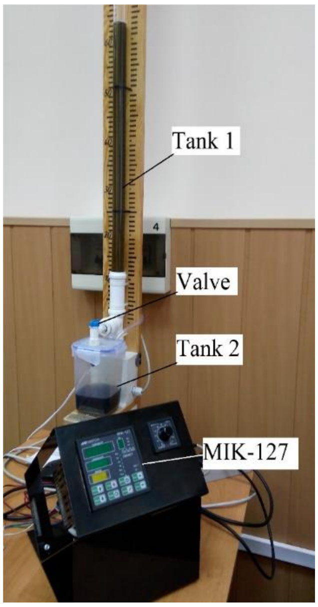


Fig. 2. **The photo of a laboratory stand for study automatic liquid level control system**
Source: **compiled by the authors**

4. COMPUTER SIMULATION OF TRANSIENT PROCESSES OF THE LIQUID LEVEL CONTROL SYSTEM

During the experiments, a computer model of the control object (Fig. 3) was created in Matlab/Simulink [20], [21], [22]. To set the parameters of the "Pump" unit (Lookup table), the control characteristic of the pump installation was used in the form of the dependence of the pump performance on the control signal [8], [18], [19].

Pump performance Q was calculated using the formula (1), where D – diameter of Tank 1 (D = 2.5 sm); t – time of liquid level change; H_{end} – final liquid level; H_{home} – initial liquid level.

For the full connected layers, the dropout operation can be described as

$$Q = \frac{(H_{end} - H_{home}) \cdot \pi \cdot D^2}{4 \cdot t}. \quad (1)$$

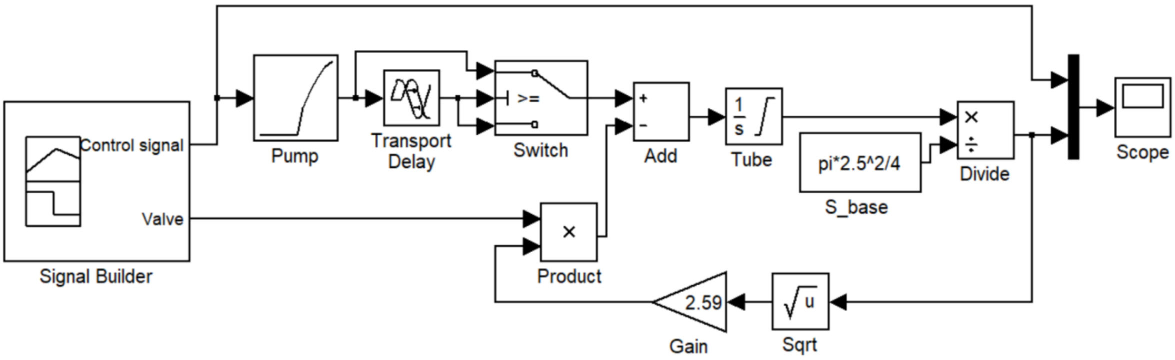


Fig. 3. **Computer model of the control object**
Source: **compiled by the authors**

The “Transport delay” and the “Switch” were used to simulate pipeline filling at start-up. The condition for switching was a positive value of the performance level at the output of the “Transport delay” block.

In order to confirm the adequacy of the computer model of the control object, an experiment was conducted, during which a fixed control signal was set for a certain period of time when the liquid drain valve was closed. After that, the liquid drain valve was opened. The results of computer modeling (Fig. 4), which were obtained during the research, were compared with the oscillogram (Fig. 5).

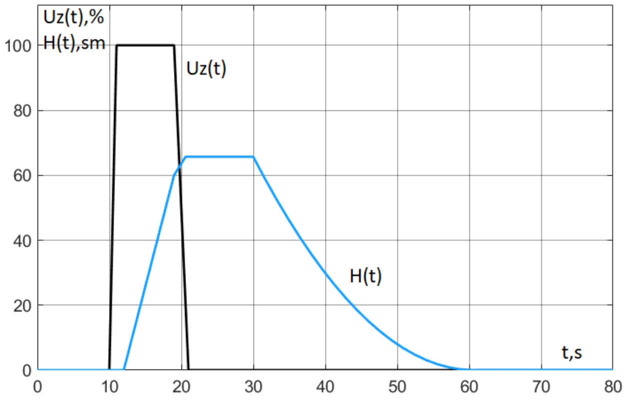


Fig. 4. **Results of computer simulation at Uz=100%; t=10 s**
Source: **compiled by the authors**

A comparison of the results of computer modeling and physical experiment confirmed the adequacy of the proposed mathematical model and gave grounds for its further use in the study of the automatic liquid level control system.

After that, the model was modified (Fig. 6) for further research, namely, to find the values of the coefficients of the PI controller [23], [24], [25] which bring the transient process of a real system with a transport delay as close as possible to the transient process of a system in which there is no transport delay [26, 27].

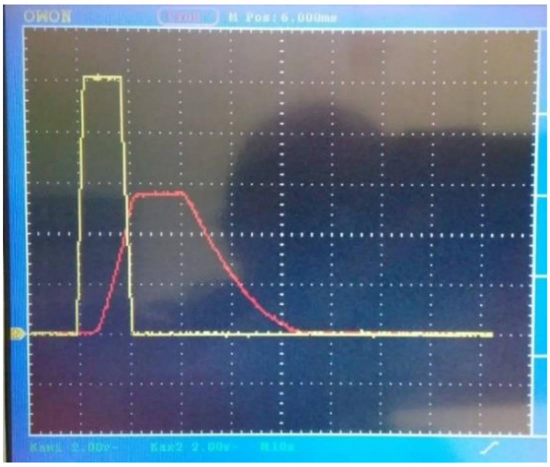


Fig. 5. **The experiment results on laboratory stand at Uz=100%; t=10 s**
Source: **compiled by the authors**

Taking into account the peculiarities of the control object, the search for optimal coefficients of the PI controller, which would provide the desired characteristics of transient processes, is proposed to be performed by minimizing the deviation of the real transient process from the target. As a criterion of optimality, in this work was used a functional of the form

$$F = \int_{t1}^{t2} \qquad (2)$$

where $f_1(t)$ – transient process of a system, which hasn`t transport delay; $f_2(t)$ – transient process of a system, which has transport delay.

Minimizing the criterion for the control voltage ensures a reduction in the amplitude of oscillations and, as a result, less wear of the pump elements. Minimization of the same criterion for the liquid level ensures an increase in the speed of the system.

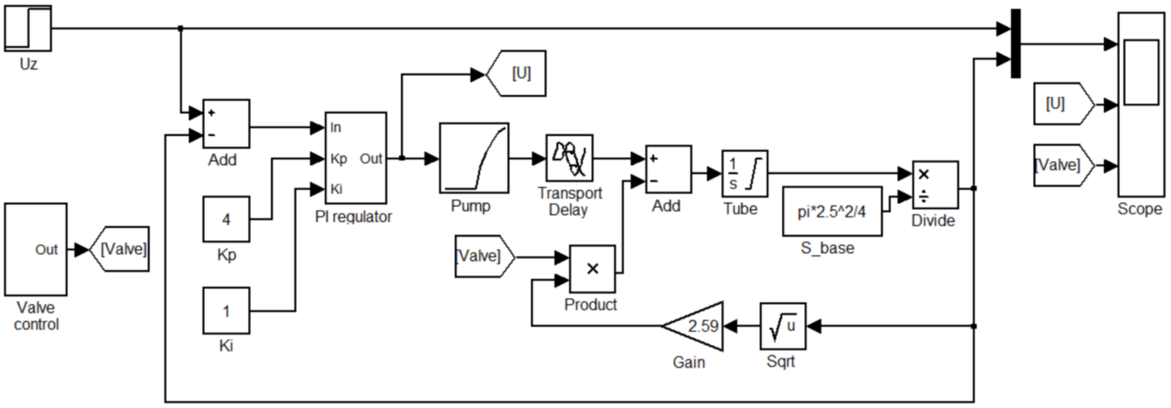


Fig. 6. **A modified computer model of the automatic liquid level control system**
Source: **compiled by the authors**

5. EXPERIMENTAL RESULTS

The transient process for the system without transport delay is taken as an exemplary (reference). In the process of modeling, the proximity of the transient process of the system with a transport delay to the transient process without a transport delay was evaluated. A functional of the form (5) was used as a closeness criterion. The simulation was carried out for values that defined four intervals of the given interval of the change of coefficients.

At the same time, the search interval for the minimum of the functional decreased as follows. The value of the functional was entered in the cells of the table (5x5), which correspond to certain values of the coefficients K_p and K_i.

The level task signal was 60 cm. The liquid drain valve from tank 1 was initially closed, then at the 20th second it was opened to 40%, then at the 40th, 60th and 80th it was opened to 60%, 80% and 100% respectively. The integration of the signal difference started from the 20th second. To find the minimum of the functional in a table of size 5x5, in which the rows correspond to the values of the integral component of the regulator (K_i), and the columns - to the values of the proportional component of the regulator (K_p), the values of the functional found by modeling were entered.

The minimum value of the functional was recorded in the center of the following table and the intervals of changing the coefficients were reduced by two times. The minimum value of the fifth table was taken as the minimum sought.

As a result of the experiments the intervals between adjacent values of the regulator coefficients were reduced by 16 times relative to the initial ones. The values of the functional for the control signal in the process of searching for the minimum are presented in the tables from 1 to 5. The values of the functional for the liquid level in the process of searching for the minimum are presented in the tables from 6 to 10.

Table 1. **The results for the control signal in the range of K_p=1-12 and K_i=1-5**

		K_p				
K_i		1	2	4	8	12
	1	35940	14950	29.02	252.3	3975
	2	66170	17750	34.43	296.4	4049
	3	125500	21390	3049	502.6	4526
	4	145100	72500	4488	641.1	4813
	5	148800	122600	6458	801.8	6095

Source: ***compiled by the authors***

Table 2. **The results for the control signal in the range of K_p = 3-5 and K_i= 0.333-1.666**

		K_p				
K_i		3	3.5	4	4.5	5
	0.333	40.74	47.73	54.05	58.95	62.36
	0.666	32.24	28.5	26.81	27.22	29.27
	1	34.99	31.66	29.02	27.39	26.78
	1.333	344.7	33.76	31.43	29.7	28.92
	1.666	3419	65.37	33.73	31.91	31.05

Source: ***compiled by the authors***

Table 3. **The results for the control signal in the range of K_p= 3.5-4.5 and K_i = 0.333-1**

		K_p				
K_i		3.5	3.75	4	4.25	4.5
	0.333	47.73	51.04	54.05	56.69	58.95
	0.499	29.37	30.27	31.75	33.65	35.83
	0.666	28.5	27.37	26.81	26.79	27.22
	0.832	30.2	28.75	27.64	26.84	26.37
	1	31.66	30.21	29.02	28.08	27.39

Source: ***compiled by the authors***

Table 4. **The results for the control signal in the range of K_p = 4.25-4.75 and K_i = 0.666-1**

	K_p					
K_i		4.25	4.375	4.5	4.625	4.75
	0.666	26.79	26.95	27.22	27.59	28.06
	0.749	26.45	26.32	26.29	26.36	26.54
	0.832	26.84	26.56	26.37	26.25	26.21
	0.915	27.43	27.09	26.81	26.61	26.47
	1	28.08	27.71	27.39	27.14	26.96

Source*: compiled by the authors*

Table 5. **The results for the control signal in the range of K_p= 4.625-4.874 and K_i= 0.749-0.915**

	K_p					
K_i		4.625	4.687	4.750	4.812	4.874
	0.749	26.360	26.440	26.540	26.660	26.800
	0.791	26.200	26.220	26.260	26.320	26.400
	0.832	26.840	26.220	26.210	26.220	26.260
	0.874	26.400	26.340	26.300	26.290	26.290
	0.915	27.430	26.530	26.470	26.430	26.410

Source*: compiled by the authors*

Table 6. **The results for the liquid level in the range of K_p= 1-12 and K_i = 1-5**

	K_p					
K_i		1	2	4	8	12
	1	1203	416.7	3.728	117.5	942.9
	2	2615	298.3	2.527	5.21	40.58
	3	3471	369.9	76.1	8.307	30.21
	4	3077	1678	74.76	9.846	32.14
	5	2675	2077	93.6	4300.00	40.03

Source*: compiled by the authors*

Table 7. **The results for the liquid level in the range of K_p = 2-8 and K_i= 1-3**

	K_p					
K_i		2	3	4	6	8
	1.0	416.70	5.25	3.73	14.66	117.50
	1.5	340.20	72.96	2.91	1.84	9.18
	2.0	298.30	163.90	2.527	1.70	5.21
	2.5	301.10	140.40	33.73	1.77	6.45
	3.0	369.90	134.00	76.10	1.70	8.31

Source*: compiled by the authors*

Table 8. **The results for the liquid level in the range of K_p= 4-8 and K_i =2.5-3.5**

	K_p

K_i		4.0	5.0	6.0	7.0	8.0
	2.5	33.73	1.94	1.77	2.53	6.45
	2.8	58.06	1.97	1.80	2.09	7.61
	3.0	76.10	2.09	1.70	2.46	8.31
	3.3	74.44	2.23	2.08	2.46	7.58
	3.5	73.59	4.33	1.73	6.71	5.60

Source*: compiled by the authors*

Table 9. **The results for the liquid level in the range of K_p = 5-7 and K_i = 2.5-3.5**

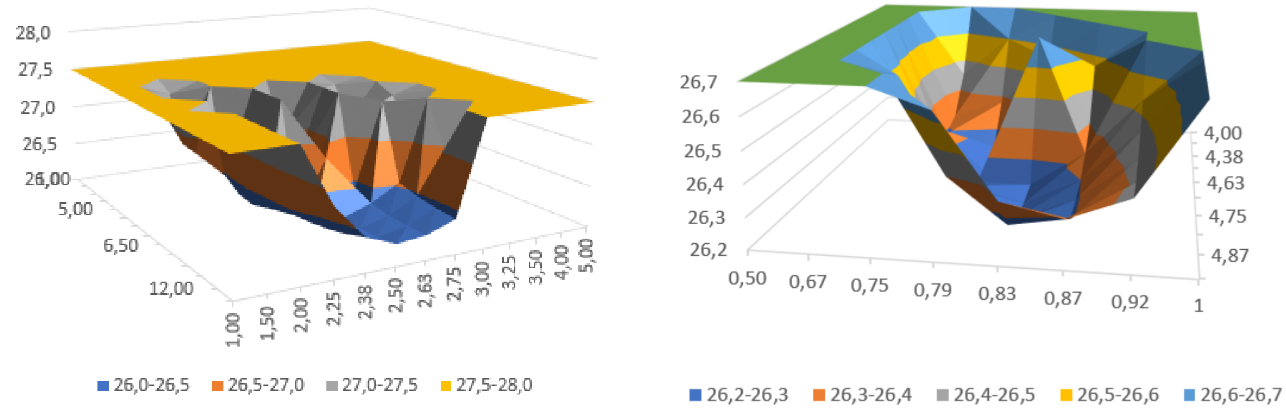
	K_p					
K_i		5.00	5.50	6.00	6.50	7.00
	2.50	1.94	1.80	1.77	1.62	2.53
	2.75	1.97	1.87	1.80	1.82	2.09
	3.00	2.09	1.77	1.70	2.27	2.46
	3.25	2.23	2.13	2.08	2.39	2.46
	3.50	4.33	1.77	1.73	1.71	6.71

Source*: compiled by the authors*

Table 10. **The results for the liquid level in the range of K_p = 6-7 and K_i = 2.25-2.75**

	K_p					
K_i		6	6.250	6.500	6.750	7
	2.250	1.717	1.635	1.607	1.808	2.729
	2.375	1.742	1.653	1.600	1.781	2.737
	2.500	1.774	1.698	1.624	1.711	2.526
	2.625	1.803	1.768	1.690	1.701	2.268
	2.750	1.803	1.859	1.819	1.787	2.087

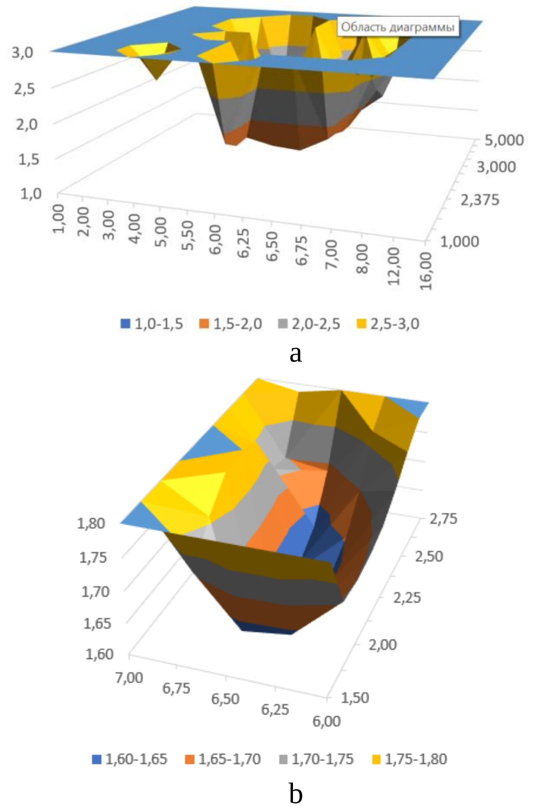
Source*: compiled by the authors*



a b

Fig. 7. **The minimization results surface functional for the control signal:
a – general view; b – enlarged fragment**

***Source:* compiled by the authors**



a

b

Fig. 8. **The minimization results surface function for the liquid level:**
a – general view; b – enlarged fragment
***Source:* compiled by the authors**

Considering the fact that there is no significant change in the value of the functional for the control signal, further searches for the coefficient and expansion of the table are not appropriate. To graphically present the results of the search for the regulator coefficients, all values of the functional obtained as a result of the simulation were placed in two tables, one for the liquid level, the other for the control signal.

In order to show the surface in detail in the vicinity of the minimum, the values of the cells that significantly exceed the minimum value were set to a certain maximum.

The maximum values for each surface were chosen for their most successful appearance. Fig. 7 and Fig. 8 shows the surfaces for the control signal and the liquid level, respectively, with Fig. 7a and Fig. 8a corresponding to the entire range, and Fig.7 b and Fig. 8b in the vicinity of the minimum.

As a result of researchment, it was established that the minimum points of the functional for the control signal and the liquid level do not coincide.

The graphs of transient processes of the control signal for the system without delay, the system with delay (K_p = 6.5, K_i = 2.375) and the system that provides the minimum value of the functional (K_p = 4.625, K_i = 0.791) are presented in Fig. 9.

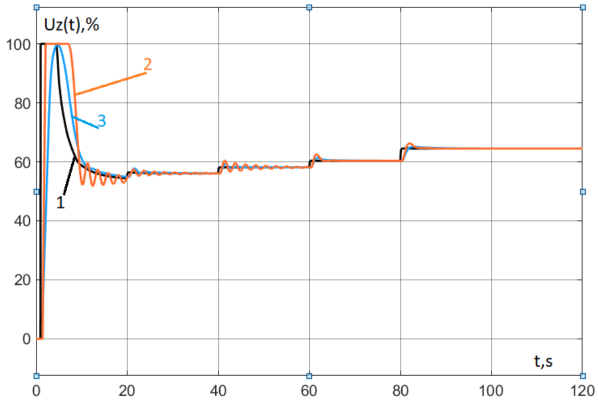


Fig. 9. **Simulation results of the control signal Uz(t) – voltage level of the control signal, expressed in %:**
1 - system without transport delay; 2 – system with transport delay; 3 – system with regulator coefficients at the functional minimum for the control signal
***Source:* compiled by the authors**

At the same time, at the minimum point of the functional for the liquid level, a larger amplitude of oscillations of the control signal is observed, and at the minimum point of the functional for the control signal – an increase in the duration of the transient process.

Therefore, the final decision should be based on the selection of priorities or optimal ratios between the speed and wear of the equipment, which is due to the instability of the control signal.

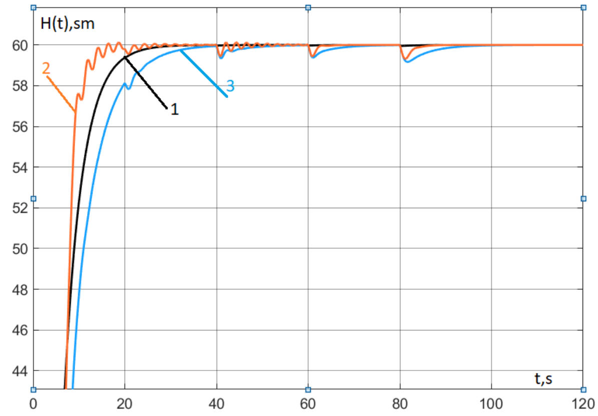


Fig. 10. **Simulation results of the liquid level H(t) – liquid level, expressed in sm:**
1 – system without transport delay; 2 – system with transport delay; 3 – system with regulator coeffiients at the functional minimum for the control signal
***Source:* compiled by the authors**

The graphs of transient processes of the liquid level for the system without delay, the system with delay (K_p = 4.625, K_i = 0.791) and the system that provides the minimum value of the functional (K_p = 6.5, K_i = 2.375) are presented in Fig. 10.

6. CONCLUSIONS

Computer model of a closed microprocessor system for automatic control of the liquid level has been developed, taking into account the nonlinearity of the characteristics of the pump installation and the transport delay, which is caused by the movement of the liquid along the tube and the location of the inlet nozzle relative to the current level of the liquid.

The use of the developed model makes it possible to search for the optimal values of the coefficients of the PI controller by minimizing the functional root-mean-square deviation of the real from the given transient processes of the pump control signal and the liquid level.

Further research will be directed to the development of a system of automated search for optimal values of the regulator coefficients, which will reduce the complexity of developing control systems for practical uses.

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Комп'ютерне моделювання мікропроцесорної системи автоматичного контролю рівня рідини

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АНОТАЦІЯ

Сьогодні автоматизація займає провідне місце в більшості галузей сучасного суспільства, майже у всіх видах промисловості та економіки. Одним із головних завдань проектування сучасних систем автоматичного керування є реалізація високих показників точності, діапазону регулювання та швидкодії з урахуванням особливостей самого об'єкта керування. Мета роботи – дослідження мікропроцесорної системи автоматичного контролю рівня рідини за допомогою комп'ютерного моделювання з урахуванням транспортної затримки, нелінійності регулювальної характеристики насоса та наявності зони нечутливості. Для досягнення мети вирішувалися наступні задачі: розроблено комп'ютерну модель замкнутої мікропроцесорної системи автоматичного контролю рівня рідини з урахуванням нелінійності характеристик насосної установки та транспортної затримки; проведено ряд експериментів з пошуку значень коефіцієнтів ПІ-регулятора, які максимально наближають перехідний процес реальної системи з транспортною затримкою до перехідного процесу системи, в якій транспортна затримка відсутня; пошук оптимальних значень коефіцієнтів ПІ-регулятора шляхом мінімізації функціоналу середньоквадратичного відхилення реальних від заданих перехідних процесів. В результаті досліджень встановлено, що точки мінімуму функціоналу для сигналу керування та рівня рідини не збігаються. При цьому в точці мінімуму функціонала від рівня рідини спостерігається більша амплітуда коливань керуючого сигналу, а в точці мінімуму функціоналу від керуючого сигналу – збільшення тривалості перехідного процесу. Тому остаточне рішення має базуватися на виборі пріоритетів або оптимальних співвідношень між швидкодією та зносом обладнання, що зумовлено нестабільністю керуючого сигналу.

Ключові слова: Система автоматичного керування; рівень рідини; мікропроцесор; комп'ютерне моделювання; ПІ-регулятор; оптимізація

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