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Робота відноситься до області оптимізації технологічних процесів, зокрема, до питань пошуку найкращого управління для систем переміщення. В рамках запропонованого методу визначається внесок процесу розгону і процесу рівномірного переміщення в формування доданої цінності досліджуваної операції. Вихід в режим оптимального управління забезпечується спеціальною процедурою визначення області, близької до точки глобального оптимуму

Ключові слова: пошук оптимального управління, оптимізація процесу переміщення, двоетапна оптимізація процесу переміщення

Работа относится к области оптимизации технологических процессов, в частности, к вопросам поиска наилучшего управления для систем перемещения. В рамках предложенного метода определяется вклад процесса разгона и процесса равномерного перемещения в формирование добавленной ценности исследуемой операции. Выход в режим оптимального управления обеспечивается специальной процедурой определения области, близкой к точке глобального оптимума

Ключевые слова: поиск оптимального управления, оптимизация процесса перемещения, двухэтапная оптимизация процесса перемещения

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DEVELOPMENT OF THE METHOD FOR DETERMINING OPTIMAL PARAMETERS OF THE PROCESS OF DISPLACEMENT OF TECHNOLOGICAL OBJECTS

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1. Introduction

Targeted improvement of operational efficiency of an industrial enterprise is possible only in the case when all its resource-intensive technological processes are optimized. In this case, optimization criteria of the managed systems must be systematically substantiated, inter-coordinated, and have to ensure maximization of financial capacity for the owner of results of operational processes (super-system).

Despite the fact that such a statement of the optimization task seems obvious, at present, managed systems integrate as optimization criteria a variety of indicators that are subjectively defined as the criteria of optimization [1].

Such indicators turn managed systems into extreme systems rather than making them optimal [2].

Among the many classes of managed systems, a special place is taken by displacement systems. The systems of this class are extremely diverse and comprise hoisting-and-transporting mechanisms [3], conveyor mechanisms for continuous transportation [4], motor transport systems [5]. They also include systems for transporting liquid and gaseous products. All these objects perform a function of the connecting link between the systems of a transformative class and the buffering systems.

A special feature of such objects is that the choice of the best parameters of a technological process is affected by

parameters of both the transient and the established displacement regime.

Different criteria of management quality are typically applied when optimizing the process of displacement under dynamic and established mode [6]. At the same time, the goal of functioning of any technological process is to maximize financial capacities of the super-system. This means that existing methods for enhancing control quality [7] are not aligned with the global aim of the super-system. Entering the mode of the global optimum, on the one hand, requires consideration of such model parameters that turn it into an essentially nonlinear one. On the other hand, the search for optimum, when employing models with essential nonlinearity, is accompanied by considerable costs arising from the work of equipment under non-optimal conditions.

Given the widespread distribution of displacement systems, as well as resource-intensive nature of displacement processes, the optimization of displacement processes is an important scientific task.

2. Literature review and problem statement

At present, the problem of displacement processes optimization is not solved as some integrity. There are known solutions to the task on searching for the best control over displacement processes with the established rate [8], and the optimization problem of transient processes [9]. In this case, in order to optimize the launch processes, PID-controllers are most commonly used, which are configured using technical criteria, specifically readjustment and adjustment time [10]. To optimize displacement processes under established mode, different energy criteria are most often applied [11].

It is believed that dynamic programming methods are rather efficient when determining an optimum in the steady displacement mode [12]. However, such an approach does not take into consideration such a factor as, for example, a dependence of the wear of equipment on the performance efficiency of a technological process.

It is known that increasing the speed or performance efficiency of any technological process leads to a nonlinear wear of system's mechanisms [13].

Thus, paper [14] gives an expression for determining the wear of electromechanical equipment during starting process on the intensity of energy product feed. Therefore, the model of an operational process, which is employed in the optimization, should take into consideration a wear factor [15] and the degree of its influence on the choice of optimal control.

For example, the classical model of a displacement system connects a job signal as an input parameter, and the motor's shaft rotation frequency as an output parameter.

Thus, the model of an electromechanical system using a d.c. electric motor (DCM) takes the form

$$\begin{cases} U_R = U_Z - k_w w, \\ \frac{dU_i}{dt} = k_i \cdot U_R, \\ U_p = k_p \cdot U_R, \\ U_d = k_d \cdot \frac{dU_R}{dt}, \\ U_F = U_i + U_p + U_d, \\ U_a = k_f \cdot U_F, \\ \frac{dI_a}{dt} = \frac{(U_a - k_e w - I_a R_a)}{L_a}, \\ \frac{dw}{dt} = \frac{(k_e I_a - T_L)}{J_a}, \end{cases}$$

where U_Z is assigning the speed;

U_R is the PID-controller input signal;

U_i is the output signal of the controller's integral part;

U_p is the output signal of the controller's proportional part;

U_d is the output signal of the controller's differential part;

U_f is the signal for setting a voltage controller;

U_a is the output voltage of converter;

I_a is the motor's anchor current;

T_L is the load of the working machine;

w is the motor's angular velocity;

k_i is the transfer coefficient of the PID-controller's integral part;

k_d is the transfer coefficient of the PID-controller's differential part;

k_p is the transfer coefficient of the PID-controller's proportional part;

k_f is the transfer coefficient of the voltage converter;

k_w is the feedback coefficient for speed;

k_e is the coefficient of motor's flow;

R_a is the active resistance of the motor's anchor chain;

L_a is the inductive resistance of the motor's anchor chain;

J_a is the motor's inertia momentum

or in the form of a block diagram consisting of transfer functions (Fig. 1).

Fig. 1 demonstrates that the effect of wear [16] in these models is not taken into consideration.

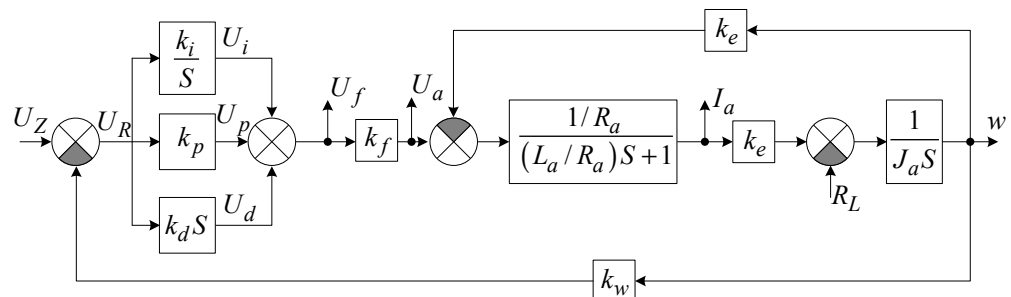


Fig. 1. Block diagram of electromechanical system based on DCM

On the other hand, an adequate technical model of the displacement system with respect to equipment wear and other kinds of input and output products ensures only a potential possibility of optimization [17].

In order to make a judgement on the effectiveness of a displacement operation, it is necessary to additionally introduce to the model scaling coefficients (cost estimates),

which make it possible to reduce quantitative parameters of the input and output products of operation to comparable magnitudes.

Hereafter, the adequate technical-economic model of the displacement system refers to such a model that makes it possible to measure not only quantitative parameters of the input and output products of operation, but their cost estimates as well.

In this sense, it is an obvious trend to employ economic indicators to solve the optimization task [18]. However, the use of KPI, for example, as a criterion of the quality of control, requires justification that the indicated indicator or a group of indicators actually defines the most favorable functioning mode of the technological process of displacement.

In this case, converting a displacement model into the technical-economic form alters it into a type of essentially non-linear models. The situation is exacerbated by the fact that the optimization criterion adds its own non-linearity. Therefore, without using specialized methods of optimization, the choice of the best control parameters can only be determined by scanning the entire range of permissible controls.

That is why the process of search optimization entails considerable costs arising from the work of equipment under non-optimal conditions, while narrowing the range of search for the optimal solution is an important task.

Therefore, the issue of the optimization of a technological process of displacement can be solved only in the case when the study is based on a technical-economic model of the operational process. In this case, the optimization should be carried out employing the agreed criterion for the quality of control, and it must prove effective.

3. The aim and objectives of the study

The aim of present work is to develop a method for determining such parameters of control that would enable the optimization of displacement processes of dynamic systems using a systematically substantiated criterion for the quality of control.

To achieve the aim, the following tasks have been set:

- to construct an adequate dynamic model of displacement on the example of electromechanical system (ES) using DCM;
- to determine a contribution of the stages of technological process of displacement to the formation of added value of the operation;
- to minimize the region of search optimization.

4. Construction of a product model of the operation of a dynamic displacement system

Operational process of any system can be always represented as its product model (Fig. 2).

This model shows that the process of displacing any object connects a product of displacement and the displacement system in time, as well as it requires consumption of energy product and is accompanied by the wear of the displacement system.

The optimization of displacement processes could be achieved in the case when a consumer of its end product is the buffering system [19]. In this case, the system of displacement acquires the necessary degrees of freedom.

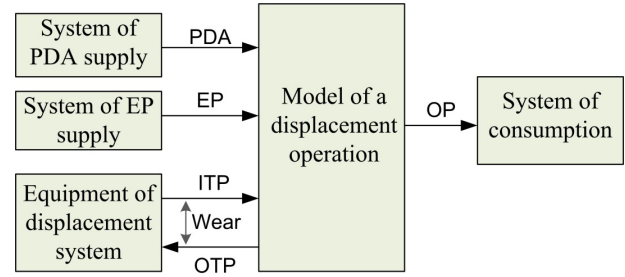


Fig. 2. Product model of displacement operation: PDA – product of directed action; OP – output product; ITP – input technological product; OTP – output technological product; EP – energy product

A transition to the product model of displacement process translates the examined model into the class of nonlinear control objects, which is associated with the non-linearity of the model of system equipment's wear and the need to determine energy cost of the operation.

A change in any control is reflected on the change in the quantitative parameters of product flows. Consequently, registration signals of quantitative parameters of product flows of the model unambiguously define technical condition of the object of study.

Thus, any operation can be identified by determining registration signal $r q_i(t)$ for each i -th input product flow and registration signal $p q_j(t)$ for each j -th output product flow.

On the other hand, in order to make a judgement on the effectiveness of displacement process, it is necessary to compare parameters of the input and output products of the examined object. This possibility is ensured by reducing quantitative parameters of the input and output products of operation to comparable cost magnitudes. Thus, we shall obtain for the input flow i and the output flow j

$$r e_i(t) = r s_i \cdot r q_i(t), \quad p e_j(t) = p s_j \cdot p q_j(t),$$

where $r s_i$ is the cost estimate of the unit of the i -th input product; $p s_j$ is the cost estimate of the unit of the j -th output product of displacement operation.

Reducing quantitative parameters of the input and output products of the product model of the operation to comparable magnitudes makes it possible in turn to pass from a product model to determining a global model of displacement operation. In a general form, operation O_f can be represented as a function of the input and a function of the output $O_f(r e(t), p e(t))$

$$r e(t) = \sum_{i=1}^J r e_i(t), \quad p e(t) = \sum_{j=1}^J p e_j(t).$$

Since the distributed character of resource use and resource yield for most displacement systems, as it was substantiated in [20], can be neglected, then the global model of displacement operation can be represented as a global model of simple operation

$$O_s(RE, TO, PE),$$

where

$$RE = \int_{t_s}^{t_f} r e(t) dt; \quad PE = \int_{t_s}^{t_f} p e(t) dt;$$

$TO=t_f-t_s$ is the duration of displacement operation.

Given the above, a technical-economic model of the displacement system equipped with a d.c. motor takes the following form

$$\left\{ \begin{aligned} U_R &= U_Z - k_e \omega, \\ \frac{dU_i}{dt} &= k_i \cdot U_R, \\ U_p &= k_p \cdot U_R, \\ U_d &= k_d \cdot \frac{dU_R}{dt}, \\ U_F &= U_i + U_p + U_d, \\ U_a &= k_F \cdot U_F, \\ \frac{dI_a}{dt} &= \frac{(U_a - k_e \omega - I_a R_a)}{L_a}; \quad \frac{d\omega}{dt} = \frac{(k_e I_a - T_L)}{J_a}, \\ \frac{dE}{dt} &= U_a I_a; \quad \frac{dW}{dt} = f(a, v), \\ re(t) &= \sum_{i=1}^I r s_i \cdot r q_i(t); \quad pe(t) = \sum_{j=1}^J p s_j \cdot p q_j(t), \\ \frac{dRE}{dt} &= re(t); \quad \frac{dPE}{dt} = pe(t), \end{aligned} \right.$$

where E are the energy costs; a, v are the instantaneous values of linear acceleration and ES displacement velocity, which are determined by the coefficient of mechanical transmission.

Mapping a displacement operation in the form of a global model of operation allows to use, as the optimization criterion, expression EL [21], which was verified for its adequacy to the formula for the efficiency of resource use [20]

$$EL = \frac{(PE - RE)^2 TP^2}{RE \cdot PE \cdot TO^2},$$

where TP is the interval of time to determine a potential effect of the operation.

However, the search for optimal control requires determining parameters of both the starting process and the process of displacement under established mode. Given the essential non-linearity of displacement model, searching for an optimum under search mode can lead to significant cost of computational resources.

A decrease in the computational cost of the search process can be ensured if the search starts from the region close enough to the global optimum.

Studies have shown that the maximum of efficiency of the operational process is located to the right of the point of minimum cost [22].

As the cost of the displacement operation equals the sum of costs of separate sections, then determining the control related to the global cost minimum comes down to sequential determining control parameters for the transient and established mode.

It was established [22] that at constant quantitative parameters of the product of targeted impact the maximum of efficiency is located to the right of the point of minimum cost. Therefore, the lower bound of the region of search optimization can be limited by controls that ensure minimal costs along an acceleration section and the section of rectilinear motion of the displacement operation.

Upon determining the lower bound of extremum search, it is possible to determine the upper bound of the region that contains the extremum based on the following considerations.

The idea of determining an upper bound of the search for the region of a global optimum is based on the assertion that is related to a special feature of the operation model estimation for the criterion of resource use efficiency. Thus, the effectiveness of an object displacement operation at a smaller distance exceeds the effectiveness of an object displacement operation at a greater distance, provided that the added value of a displacement operation is proportional to the distance of displacement.

We shall prove the following *theorem*. Under condition of a proportional increase in the cost estimation of the output product, depending on the distance of displacement, and at uniform rate of displacement, the displacement operation to distance S (operation A) is more efficient than the displacement operation to distance kS (operation B), where $k > 1$.

Proof. Assume that cost estimates of the input and output products RE, PE and operation time T_O are assigned for the operation of uniform displacement of an object to distance S . Then, for the operation over displacement distance kS , the respective cost estimates are equal to kRE and kPE at operation duration kT_O .

For operation A, the effectiveness is determined from expression

$$EL_A = \frac{(PE_A - RE_A)^2 TP^2}{RE_A \cdot PE_A \cdot TO_A^2}.$$

We shall derive the efficiency of operation B

$$\begin{aligned} EL_A &= \frac{(kPE_A - kRE_A)^2 TP^2}{kRE_A \cdot kPE_A \cdot (kTO_A)^2} = \\ &= \frac{k^2 (PE_A - RE_A)^2 TP^2}{k^2 RE_A \cdot PE_A \cdot k^2 (TO_A)^2} = \frac{1}{k^2} EL_A. \end{aligned}$$

Because under condition of the theorem $k > 1$, then $EL_B < EL_A$ for any values of operation parameters.

The theorem is proven.

Thus, the upper bound of the region of search for an extremum can be limited by the controls that ensure maximum efficiency for separate sections of the displacement operation.

However, it is necessary to take into consideration that, in the process of entering the established mode, the displacement system simultaneously solves both the task of displacement and the task on increasing potential energy of the displaced object.

Thus, the task on entering a mode of optimal control in the displacement systems requires determining the added value, which is transferred by the displacement system to the displaced object both in the process of entering the established mode and in the process of the established mode.

In order to determine the added value of a dynamic mode, we shall determine parameters of the acceleration operation. Specifically, the time of acceleration operation to the speed that ensures minimum cost in the established mode and the cost of the start-up process.

Upon determining the cost of the displacement process in the established mode for the time of acceleration, we shall

obtain a cost estimate of the start-up process, which enabled the transfer of the required amount of kinetic energy to the displaced object.

Based on known magnitude of the added value of operational process of a technological object displacement, it is possible to determine a magnitude of the added value of the process of uniform displacement. Considering that for the established rate of displacement the magnitude of potential energy, depending on the intensity of acceleration, does not change, it is possible to determine the magnitude of the added value of the process of uniform displacement

$$\alpha = \frac{RE_a}{RE_a + RE_s}; PE_a = \alpha \cdot PE; PE_s = (1 - \alpha)PE.$$

Based on the above formulae, we constructed in the Matlab/Simulink programming environment a mathematical model to determine the indicator of effectiveness of the displacement process (Fig. 3).

We used as a drive DCM the d.c. motor with independent excitation of the type PBK-380/65 with the following specifications: rated power is 1,300 kW; rotation frequency is 38 rpm; nominal voltage is 600 V.

We employed as controlling variables the values for the established displacement rate v_0 , m/s, and acceleration a_0 , m/s², at which the motor was accelerated to the established speed. In practice, these variables are set by adjusting parameters of PID-controller.

We investigated the operation that involved a load displacement to a distance of 110 m. STOP module is designed to automatically stop simulation upon reaching the preset displacement.

Fig. 4 shows diagrams of the work of a mathematical model for determining the indicators of displacement operation.

Fig. 5 shows a dependence, obtained during experiments on the mathematical model, of the efficiency of displacement process on parameters of separate stages of the displacement operation.

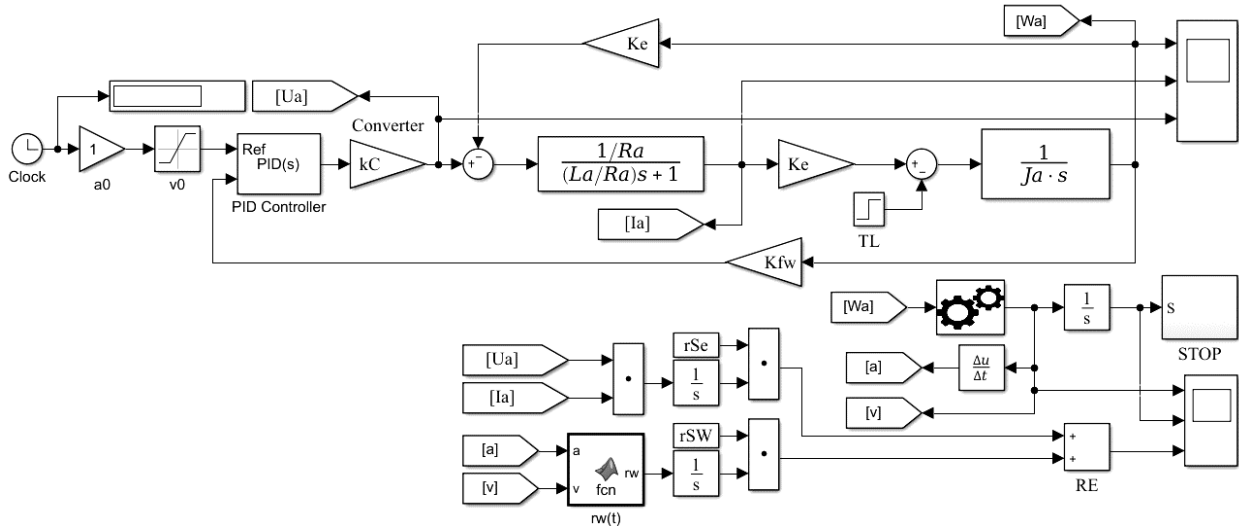


Fig. 3. Implementation of the mathematical model for determining the indicators of displacement operation, realized in Matlab/Simulink

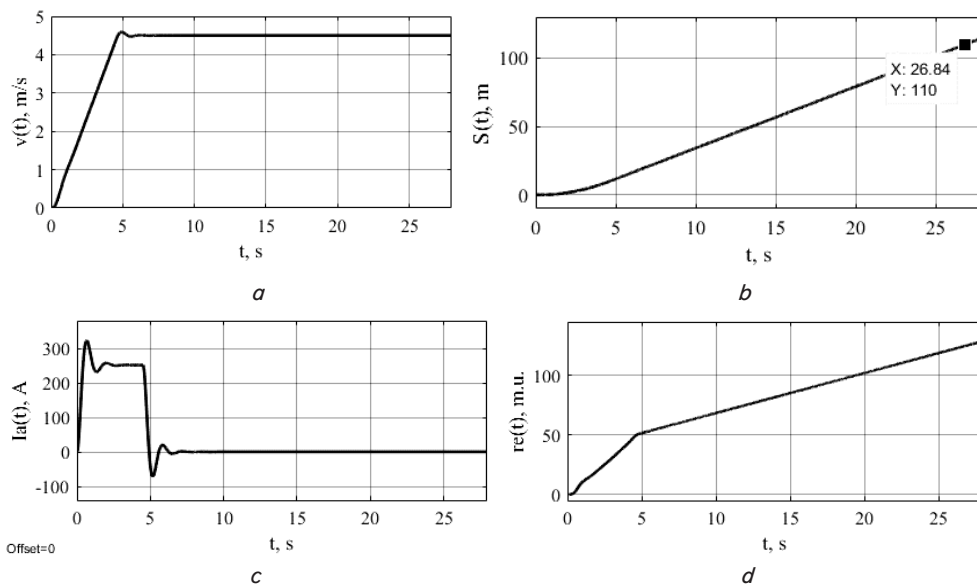


Fig. 4. Time charts of displacement operation: *a* – linear displacement speed, m/s; *b* – traveled path, m; *c* – drive motor’s anchor current, A; *d* – cost estimate of input resources, monetary unit

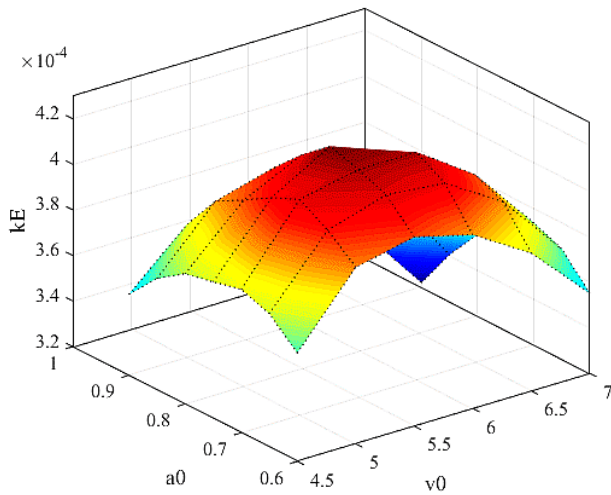


Fig. 5. Dependence of the efficiency of displacement process on acceleration a_0 and established velocity v_0 of the displacement operation

Fig. 6 shows results of implementation of the proposed algorithm for searching an extremum of efficiency indicator of the displacement operation.

The region of permissible controls is a rectangle with sides $0.3 < a_0 < 1$; $3 < v_0 < 10$.

In line with the above procedure, we first search for the lower bound of the refined region of search for extremum S , which optimizes a minimum of the start-up operation costs. Upon performing a series of numerical experiments on the model in Fig. 3, we determine the coordinates of point S (4.5; 0.65). Then we determine point F – the upper bound of the refined region of search for an extremum, which indicates the maximum of efficiency indicator for separate sections of the displacement operation. Upon performing a series of numerical experiments on the model in Fig. 3, we find the coordinates of point F – (7; 0.9). The middle of section $[SF]$ is point M at coordinates $((4.5+7)/2; (0.65+0.9)/2) = (5.75; 0.775)$. As shown by the numerical experiments on the mathematical model in Fig. 3, the maximum value of efficiency indicator kE is located at point O at coordinates (5.5, 0.75). As the coordinates of points S and F can be found with a sufficient accuracy by analytical methods when using the piecewise-linear motion patterns, then the application of the proposed algorithm significantly narrows the search region and improves performance efficiency when searching for an extremum.

The application of the improved algorithm for searching an extremum of efficiency indicator of the displacement operation allowed us to decrease by more than 7 times the area of the region of extremum search. The initial area of the rectangle of permissible controls comprised 4.9 conditional units. As a result of the use of the proposed method the search area was reduced to 0.625 conditional units. The area of the refined extremum search is restricted by points S and F (Fig. 6). An additional advantage of the proposed method is that it is easy to determine a starting point of the search that is the middle of section SF , which is located in close proximity to the global extremum of efficiency indicator of displacement process.

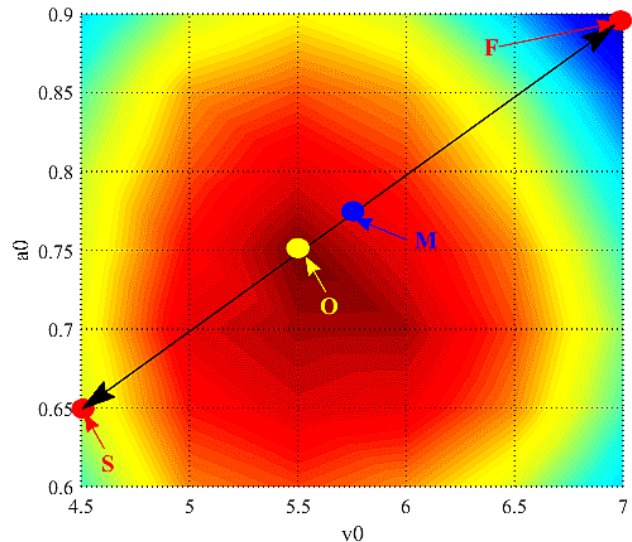


Fig. 6. To explain the improved algorithm of search for an extremum of efficiency indicator of the displacement operation

8. Discussion of results of research into determining optimal trajectory of control over displacement process

A distinctive feature of the displacement systems is that parameters of optimal control are defined both by the choice of acceleration mode and the choice of the established mode. Within the framework of present study, the best control parameters are selected with respect to determining a technical-economic model and employing a single systemically-substantiated optimization criterion.

Such an approach makes it possible, provided an adequate model of the examined object is constructed, to obtain a truly useful effect from the results of optimization.

Since the optimization model is essentially non-linear, the only reliable method of reaching a global optimum point is the search optimization. In this case, the use of classical methods of the optimization process requires a substantial narrowing of the region of initial search.

The proposed method does solve this task. A distinctive feature of the method is the high degree of symmetry of the determined bounds, which in fact ensures reaching the optimum region over one step of iteration.

Here, the optimum region refers to such parameters of displacement process whose change within the optimum range does not yield the guaranteed best result because of the model's errors, or errors of sensors for measuring quantitative and qualitative parameters of the technological process of displacement.

Certainly, within the framework of the present study we made an assumption about the linearity of the acceleration process. On the one hand, it allowed us to determine clear-cut limits of operational sub-processes of acceleration and displacement at constant speed. On the other hand, the process of acceleration requires determining not so much of an optimum but determining an optimal trajectory. Solving this problem is planned in the course of further research.

The present research is continuation of the studies related to the development of optimization methods and search for optimal trajectories of control [23].

9. Conclusions

1. We have identified important factors that impact the principles of choosing an optimal control over displacement systems, and constructed a mathematical model of electro-mechanical systems of displacement based on a d.c. electric drive. We have built a model of the displacement system, which takes into consideration the wear of mechanisms of an electromechanical system and cost estimates of the input and output products of displacement operation.

2. We have determined the contribution of stages of the technological displacement process to the creation of the added value of the operation, which made it possible to determine the upper bound of the refined region of search

for an extremum of efficiency indicator of the displacement operation.

3. We have developed a method to limit the region of search for a global optimum in the system of displacement of technological objects. Its special feature is the narrowing of the region of a two-parametric search optimization of the displacement process by a preliminary four-stage one-parametric search for local extrema for the sub-processes of acceleration and the process of uniform displacement. In this case, within the framework of the first and second stage of search for local minima of the sub-processes costs, we determine initial conditions in the search for the local maxima of efficiency of the sub-processes of displacement.

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Запропоновано комплексний підхід щодо визначення рівня безпеки руху поїздів на об'єктах залізничної інфраструктури. Підхід передбачає урахування різних факторів впливу: технічні засоби, робота з персоналом, технологія роботи, грошові витрати у безпеку руху. Кожний фактор характеризується показниками з різними розмірностями. Дану задачу запропоновано вирішувати з використанням адитивного результуючого показника. Запропонований у роботі метод забезпечить більш якісний аналіз ситуації. Існує можливість виявити небезпечні об'єкти, що впливають загалом на рівень безпеки залізниці

Ключові слова: безпека руху, метод оцінки рівня безпеки руху, комплексний показник

Предложен комплексный подход к определению уровня безопасности движения поездов на объектах железнодорожной инфраструктуры. Подход предполагает учет разных факторов воздействия: технические средства, работа с персоналом, технология работы, денежные затраты в безопасность движения. Каждый фактор характеризуется показателями с различными размерностями. Данную задачу предложено решать с использованием аддитивного результирующего показателя. Предложенный в работе метод обеспечит более качественный анализ ситуации. Существует возможность выявить опасные объекты, влияющие в целом на уровень безопасности железной дороги

Ключевые слова: уровень безопасности движения, комплексный показатель, метод оценки уровня безопасности движения

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EVALUATION OF THE RAILWAY TRAFFIC SAFETY LEVEL USING THE ADDITIVE RESULTANT INDICATOR

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1. Introduction

Ensuring traffic safety of Ukrainian railway transport is an important factor of joining the European trade zone [1]. However, the level of safety on Ukrainian railways does not meet present-day requirements and the accident rate is much worse compared to EU countries. The number of transport events tends to decrease from year to year but the losses caused by them remain almost at the same level.

Repetition of transport events from year to year and pre-conditions to their occurrence is the evidence of inadequacy of the existing system of transportation safety management.

It does not ensure the interest of employees in the qualitative performance of technological processes, does not reveal violations, or prevent their consequences.

The existing railway traffic safety system in Ukraine is not able to cover all necessary production and operation processes on which guarantee of safety depends.

Safety management requires new approaches implementation of which should introduce essential adjustments to the current system of transportation safety management.

The priority lines of development of Ukrainian railway transport include rise of the railway traffic safety level and harmonization with EU transport legislation.