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МОДЕЛИРОВАНИЕ СИСТЕМЫ МЕЖДУГОРОДНЫХ ПАССАЖИРСКИХ ПЕРЕВОЗОК

Исследованы средства проведения оценки параметров эффективности функционирования системы маршрутов пассажирских транспортных систем. Предложена последовательность формирования транспортной системы междугородного пассажирского транспорта, которая опирается на достижения науки и практики и учитывает закономерности распределения транспортных корреспонденций между городами от транспортной сети. Дополнена функция притяжения между городами в соответствии с количеством жителей и покупательной способностью.

Ключевые слова: система маршрутов, эффективность перевозок, пассажирские корреспонденции, транспортный процесс.

Dolya Constantine, *PhD, Senior Lecturer, Department of GIS, Land and Real Estate Appraisal, O. M. Beketov National University of Urban Economy in Kharkiv, Ukraine, e-mail: k.dolya@inbox.ru, ORCID: http://orcid.org/0000-0002-4693-9158*

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Zhuchenko O.

CONTROL SYSTEM SYNTHESIS OF FORMATION OF CARBON PRODUCTS

Запропонована нова система керування, яка передбачає керування з ітеративним навчанням (КІН) процесом формування продавлюванням електродної маси через мундштук відповідної форми у гідравлічному пресі. Запропоновано відповідний КІН-алгоритм. Дане дослідження підтвердило, що КІН-алгоритм забезпечує високу якість керування в умовах відсутності початкових невизначеностей та зовнішніх збурень.

Ключові слова: *вуглецеві вироби, керування з ітеративним навчанням (КІН), система керування, КІН-алгоритм.*

1. Introduction

Consumers of carbon products are various industries in which production is associated with the need for the use of electrothermal technological processes. In particular, such enterprises include enterprises of ferrous and nonferrous metallurgy, machine building, chemical industry and others.

The production of carbon products is characterized by considerable resource and energy intensity, therefore the actual task is to increase the efficiency of this production by introducing the optimum operating modes of its component technological processes. The solution of this problem involves experimental studies of technological processes, including through simulation modeling and research, the results of which should be created and implemented an optimal control system.

2. The object of research and its technological audit

The object of research is the process of formation of carbon products.

One of the main technological processes in the production of carbon products is the process of their formation by squeezing of the electrode mass through a mouthpiece of the corresponding shape in a hydraulic press. All inherited properties that determine the quality of finished products are laid at the stage of pressing the electrode blanks [1, 2].

When conducting the process, it is necessary to provide a specified temperature regime, so the process of formation of carbon products is characterized by significant energy intensity. Therefore, the actual task is to increase its efficiency by introducing optimal energy-saving modes of operation [2]. The solution of this problem involves the creation of an effective system for the optimal control of this process.

3. The aim and objectives of research

The aim of this research is to study practical aspects of the implementation of iterative learning control (ILC) algorithms as part of the control system for the process of carbon products and the adjustment of such system.

To achieve this aim, it is necessary to perform the following tasks:

1. To analyze the formation process from the point of view of its control.
2. To carry out the synthesis of the corresponding control system, which will meet the resource and energy saving requirements using the ILC algorithm.

4. Research of existing solution of the problem

In work [3], a strategy for the optimal switching of heaters is developed, which ensures the heating of the press with insignificant temperature overheating. To effectively stabilize the temperature of the formation process, control methods [4–6] based on the predictive model are proposed. In [7–9], multidimensional control systems are presented, the purpose of which is to compensate for perturbations acting in the regime of heating the press.

The process of formation of carbon products is a typical cyclic process. For such processes, the control task is, as a rule, to implement such controls that would ensure that one or more output variables are tracked by a predetermined path of motion, which is repeated from cycle to cycle. This task can be performed by a standard PID controller. However, the lack of such management is that this does not take into account the experience gained in previous operation cycles.

Thereby, it seems expedient to apply the iterative learning control [10–14]. This method just provides for the formation of controls not only for the error of the current control, but also for information from previous operation cycles. The main task of ILC is to create an algorithm that generates control signals in such way that the quality of control is improved from one cycle of operation (iteration) to the next.

The notion of iterative learning control was first introduced in [10], and later mathematically formulated in [11]. Since then, much effort has been made to develop and research this control method. ILC was used to control many objects, such as reactors and distillation columns of batch action, pressing [12, 15, 16].

Taking into account the conducted analysis, it is expedient to apply control elements with iterative training in the control system of formation of carbon products.

5. Methods of research

It is assumed that the control object is mathematically described in the state space by a discrete model:

$$\begin{aligned}
&x_k(t+1) = Ax_k(t) + Bu_k(t) + \nu_k(t),\\
&0 \le t \le N,\ k = 0,\ 1,\ 2,\ \dots,\\
&y_k(t) = Cx_k(t) + \omega_k(t),\\
&x_k \in \Re^n,\ u_k \in \Re^m, y_k \in \Re^p,
\end{aligned} \tag{1}$$

where k is the iteration number (operation cycle); t is the current time. Thus, $y_k(t)$ is the output of the control object at time t in the k-th operation cycle. $v_k(t)$ and $w_k(t)$ are limited perturbations acting on the state and output of the object, respectively. For simplicity, let's assume that the matrices A, B and C are stationary.

Using equations (1), obtain:

$$y_k(t) = \sum_{l=0}^{t-1} CA^{t-1-l} Bu_k(l) + h_k(t), \tag{2}$$

$$h_k(t) = CA^t x_k(0) + \sum_{l=0}^{t-1} CA^{t-1-l} v_k(l) + w_k(t). \tag{3}$$

Equations (2) and (3) can be rewritten in the matrix form:

$$y_k = Gu_k + \eta_k, \tag{4}$$

where

$$y_k = \begin{bmatrix} y_k(1) \\ y_k(2) \\ \vdots \\ y_k(N) \end{bmatrix},\quad u_k = \begin{bmatrix} u_k(0) \\ u_k(1) \\ \vdots \\ u_k(N-1) \end{bmatrix},\quad \eta_k = \begin{bmatrix} \eta_k(1) \\ \eta_k(2) \\ \vdots \\ \eta_k(N) \end{bmatrix},$$

$$G = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{N-1} & CA^{N-2}B & \cdots & CB \end{bmatrix}.$$

In the last expressions, the argument t is omitted. The matrix G is the lower triangular block matrix known as the Toeplitz matrix [13, 17]. According to algorithm, y_k and u_k of the previous cycle should be remembered for calculating $u_{k+1}(t)$ of the current cycle.

In the absence of perturbations and errors of the initial state, system (1) becomes the form:

$$\begin{aligned}&\hat{x}_k(t+1)=A\hat{x}_k(t)+Bu_k(t),\\&0\le t\le N,\ k=0,\ 1,\ 2,\ \ldots,\\&\hat{y}_k(t)=C\hat{x}_k(t),\\&\hat{x}_k\in\Re^n,\ u_k\in\Re^m,\hat{y}_k\in\Re^p,\end{aligned}\qquad(5)$$

where variables marked « ∧ » mean «ideal» state variables and output variables calculated under the conditions of absence of perturbations and errors of the initial state.

For the given output of the system in (k+1)-th cycle of operation on interval $1\le t\le N$, the ideal optimal ILC is determined by minimization according to the $u_{k+1}(t)$ of following quadratic quality criterion:

$$\begin{aligned}J_{k+1}=&\sum_{t=1}^{N}[r(t)\text{-}\hat{y}_{k+1}(t)]^TQ(t)[r(t)-\hat{y}_{k+1}(t)]+\\&+\sum_{t=0}^{N-1}[\Delta u_{k+1}(t)]^TR(t)[\Delta u_{k+1}(t)],\end{aligned}\qquad(6)$$

where $\Delta u_{k+1}(t)=u_{k+1}(t)-u_k(t)$, and the weight matrices $Q(t)$ and $R(t)$ are arbitrary symmetric positive definite for all.

The quality criterion (6) can be rewritten in the matrix form:

$$J_{k+1}=[r-\hat{y}_{k+1}]^TQ[r-\hat{y}_{k+1}]+\Delta u^T{}_{k+1}R\Delta u_{k+1},\qquad(7)$$

where

$$\begin{aligned}&Q=\mathrm{diag}\{Q(1),Q(2),\ldots,Q(N)\},\\&R=\mathrm{diag}\{R(0),R(1,\ldots,R(N\text{-}1)\},\end{aligned}$$

and

$$\hat{y}_k=\begin{bmatrix}\hat{y}_k(1)\\\hat{y}_k(2)\\\vdots\\\hat{y}_k(N)\end{bmatrix},\ r=\begin{bmatrix}r(1)\\r(2)\\\vdots\\r(N)\end{bmatrix}.\qquad(8)$$

Finding the derivative with respect to u_{k+1} in expression (7), let's obtain an ideal optimal control:

$$\hat{u}_{k+1}=\hat{u}_k+R^{-1}G^TQ[r-y_{k+1}].\qquad(9)$$

For the conditions for the absence of perturbations and errors of the initial state, an analogous control algorithm is proposed in [18]:

$$\begin{aligned}&S(t)=A^TS(t+1)\{I-B[B^TS(t+1)B+R(t+1)]^{-1}\times\\&\times B^TS(t+1)\}A+C^TQ(t+1)C,\\&t=0,1,\ldots,N-1;S(N)=0,\end{aligned}\qquad(10)$$

$$\begin{aligned}&\phi_{k+1}(t)=[I+S(t)BR^{-1}(t)B^T]^{-1}[A^T\times\phi_{k+1}(t+1)+\\&+C^TQ(t+1)\hat{e}_k(t+1)],\\&t=0,1,\ldots,N-1;\ \phi_{k+1}(N)=0,\end{aligned}\qquad(11)$$

where $\hat{e}_k(t+1)=r(t+1)-\hat{y}_k(t+1)$.

According to [5], the optimal control is calculated by the formula:

$$\begin{aligned}&\hat{u}_{k+1}(t)=\hat{u}_k(t)-\\&-[B^TS(t)B+R(t)]^{-1}B^T\times S(t)A[\hat{x}_{k+1}(t)-\hat{x}_k(t)]+\\&+R^{-1}(t)B^T\phi_{k+1}(t).\end{aligned}\qquad(12)$$

This expression indicates that the ideal control can be determined iteratively using the ideal value of the state variables $\hat{x}_k$ and $\hat{y}_k$ with (5).

Under industrial conditions, there are always uncertainties in the operating disturbances, and also not always the next cycle of operation completely repeats the previous one, because the technological parameters and the material quality parameters may differ for each cycle.

In the presence of perturbations and errors of the initial state, the calculation must be carried out according to equations (10)–(12) with the replacement of the quantities $\hat{x}_k$ and $\hat{y}_k$ by the quantities $\hat{x}_k$ and $\hat{y}_k$, respectively, determined from the model (1). Hence, the control law is written as:

$$u_{k+1}=u_k+R^{-1}G^TQe_{k+1},\qquad(13)$$

$$\begin{aligned}&\phi_{k+1}(t)=[I+S(t)BR^{-1}(t)B^T]^{-1}\times\\&\times[A^T\phi_{k+1}(t+1)+C^TQ(t+1)e_k(t+1)],\\&t=0,1,\ldots,N-1;\ \phi_{k+1}(N)=0,\end{aligned}\qquad(14)$$

$$\begin{aligned}&u_{k+1}(t)=u_k(t)-\\&-[B^TS(t)B+R(t)]^{-1}B^T\times S(t)A[x_{k+1}(t)-x_k(t)]+\\&+R^{-1}(t)B^T\phi_{k+1}(t),\end{aligned}\qquad(15)$$

where $S(t)$ obtain from equation (10).

An important role in ensuring the robustness and convergence of the above control algorithm is played the choice of matrices Q and R. Let's suppose:

$R=\lambda I$ and $Q=\mu I$,

where λ and μ – positive constants.

Let's denote $\rho=\dfrac{\mu}{\lambda}$.

The choice of λ and μ values should ensure the robust stability of the control system.

From the equations (13)–(15) we have:

$$u_{k+1}=(I+\rho G^TG)^{-k}u_0+\sum_{l=1}^{k}\rho(I+\rho G^TG)^{-l}G^T(r-\eta_{k+2-l}),$$

$$e_{k+1}=(I+\rho GG^T)^{-k}e_0-\sum_{l=1}^{k}(I+\rho GG^T)^{-l}\Delta\eta_{k+2-l}.$$

Thus, we obtain a description of the ideal control law.

6. Research results

The efficiency of ILC algorithms is studied using the example of a system for controlling the rate of formation of carbon products. For this purpose, a mathematic model of autoregression – moving average – is built using MatLab Simulink and Control System Toolbox [19]. This model connects the control signal of the press drive with the pressing speed. After the transformation to the model in the state space, this model has the form:

$$x(t+1)=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0.22 & 0.65\end{bmatrix}x(t)+\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}u(t),$$

$$y(t)=\begin{bmatrix}-98.2 & 147.37 & 0\end{bmatrix}x(t). \qquad (16)$$

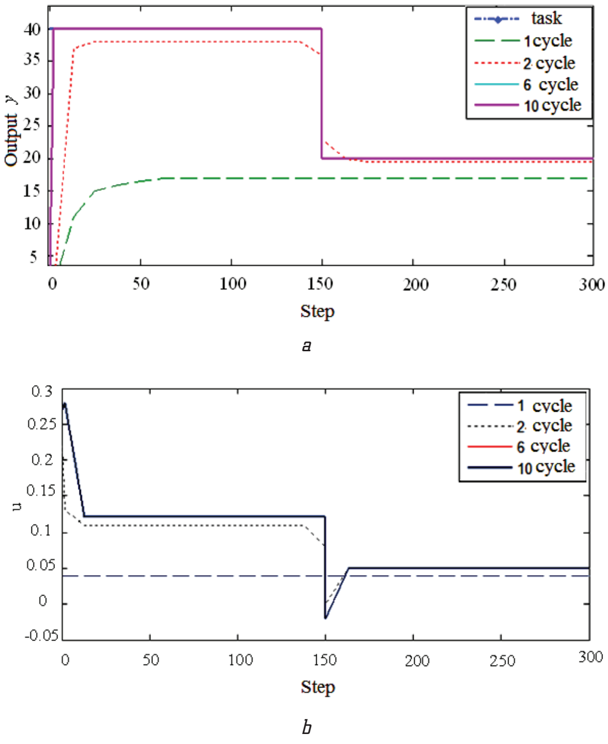
As follows from (16), first a system, in which external perturbations do not act, is studied.

The above-mentioned ILC algorithm with the settings $Q=R=1$ is applied to the system (16).

The signal of the task, which the monitoring system should monitor, changes, as shown in Fig. 1, *a*, by a continuous line.

The control signal shown in Fig. 1, *b*, and in the first operation cycle is equal to 0.04. As can be seen from Fig. 1, *a*, in the first operation cycle the output signal is far from the target.

However, the control system demonstrates high convergence already in the second cycle of operation. The output signal of the system in the sixth and tenth cycles indicates a clear tracking of the task (the trajectory in the 6th and 10th cycles is superimposed).



a

b

Fig. 1. Simulation results: *a* – output variables; *b* – control

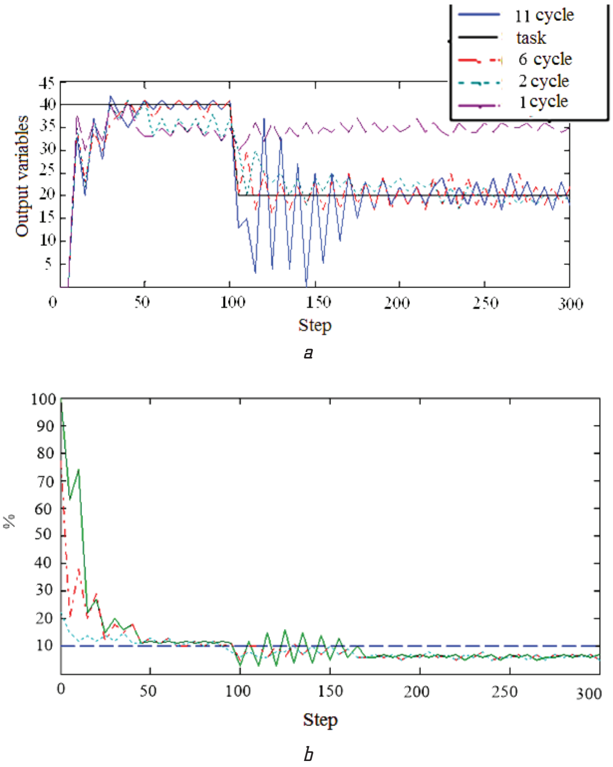
The study is conducted for 10 operation cycles. This confirmed that ILC algorithm provides a high quality control in the absence of initial uncertainties and external disturbances.

Further, the study is carried out taking into account the effect of external perturbations.

At the first stage of the study, the matrices are chosen to be the same as in the previous case, and did not change throughout the study.

Fig. 2 shows the changes in the output signal (*a*) and control (*b*) (control signal expressed as a percentage of its change range).

As can be seen from Fig. 2, *a*, the output signal becomes oscillating with increasing amplitude of oscillations during transition from one operation cycle to the next (with increase), in contrast to the results obtained earlier.



a

b

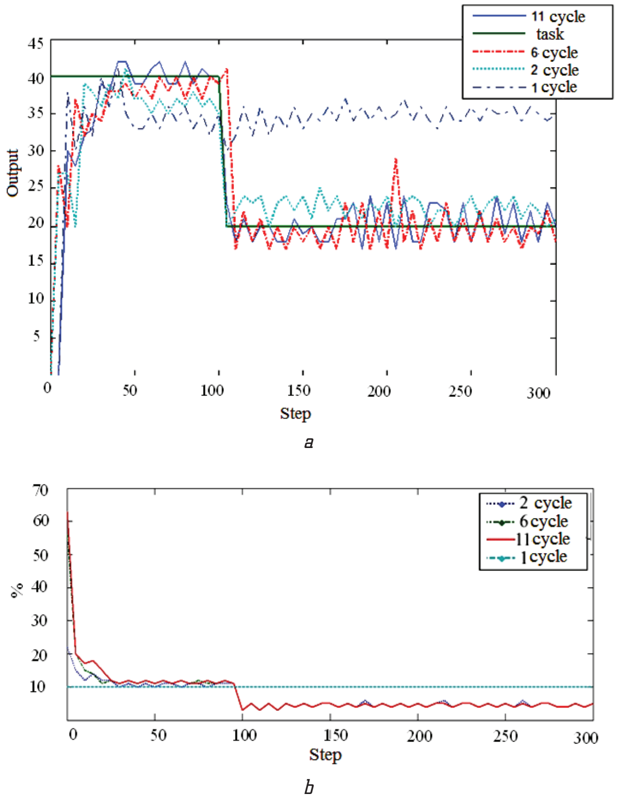
Fig. 2. Simulation results: *a* – output variables; *b* – control

At the second stage of the study, a modified ILC algorithm with the introduction of a variable setting parameter ρ is used. $\rho=1$ in the first cycle of operation. In the following cycles, ρ decreases according to the exponential law: $\rho=0.6^{k-1}$.

The corresponding output and control signals are shown in Fig. 3.

As can be seen from Fig. 3, a rapid convergence of the control algorithm is observed in the second cycle of operation. Already in the sixth cycle, the output signal is close enough to the given one, and in the tenth it actually repeats it.

The study is conducted for 11 cycles of equipment operation. Thus, the use of the modified ILC algorithm allows to eliminate the oscillations of the output signal, providing rapid convergence to a given trajectory of motion with k increase and stability of the control system.



a

b

Fig. 3. Simulation results with the introduction of a variable setting parameter: *a* – output variables; *b* – control

7. SWOT analysis of research results

Strengths. The task of building a control system for the process of formation of carbon products using ILC algorithm is solved. This control system makes it possible to eliminate fluctuations in the output signal, ensures rapid convergence to a given trajectory of motion with k increase and stability of the control system, which affected the efficiency of the process.

Unlike analogues, the proposed control system will allow increasing the technological indicators of process quality, which in the subsequent stages of production of carbon products will significantly affect the quality of the final product.

Weaknesses. The developed control system should be tested for efficiency. Studies on existing equipment to confirm the effectiveness will be carried out in the following author's studies. When this research is introduced into production, it may be accompanied by economic losses due to the probability of creating an emergency situation, etc.

Opportunities. Verification of the effectiveness of the proposed control system and its correction based on the obtained results is the task of further research. This control system will significantly improve the quality of products at the subsequent stages of production of carbon products.

Threats. Using a control system with ILC algorithm elements will require additional costs for the purchase of modern computer tools and software.

8. Conclusions

1. The analysis of the existing control systems for the process of formation of carbon products shows that the formation process is a typical cyclic process. For such processes, the control task is, as a rule, to implement such controls that would ensure that one or more output variables are tracked by a predetermined path of motion, which is repeated from cycle to cycle. Thereby, it seems expedient to apply the iterative learning control.

A new control system is proposed that provides for iterative learning control in formation of the electrode mass by squeezing through a mouthpiece of the corresponding shape in a hydraulic press.

2. The corresponding ILC algorithm is obtained. This study confirms that ILC algorithm provides a high quality control in the absence of initial uncertainties and external disturbances. Further, the investigation is carried out taking into account the effect of external perturbations. At the second stage of the study, a modified ILC algorithm with the introduction of a variable setting parameter ρ is used. The use of the modified ILC algorithm allows to eliminate the oscillations of the output signal, providing rapid convergence to a given trajectory of motion with k increase and stability of the control system.

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СИНТЕЗ СИСТЕМЫ УПРАВЛЕНИЯ ПРОЦЕССОМ ФОРМИРОВАНИЯ УГЛЕРОДНЫХ ИЗДЕЛИЙ

Предложена новая система управления, которая предусматривает управление с итеративным обучением (УИО) процессом формирования продавливанием электродной массы через мундштук соответствующей формы в гидравлическом прессе. Предложен соответствующий УИО-алгоритм. Данное исследование подтвердило, что УИО-алгоритм обеспечивает высокое качество управления в условиях отсутствия начальных неопределенностей и внешних возмущений.

Ключевые слова: углеродные изделия, управления с итеративным обучением (УИО), система управления, УИО-алгоритм.

Zhuchenko Oleksii, *PhD, Associate Professor, Department of Chemical Automation Manufactures, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: azhuch@ukr.net, ORCID: http://orcid.org/0000-0001-5611-6529*