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THE METHOD OF AUTOMATIC CONTROL SYSTEM SYNTHESIS ON THE BASE OF DISCRETE TIME EQUALIZER

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МЕТОД СИНТЕЗУ СИСТЕМ АВТОМАТИЧНОГО КЕРУВАННЯ НА БАЗІ ДИСКРЕТНОГО ЧАСОВОГО ЕКВАЛАЙЗЕРА

Purpose. Development of a synthesis method for automatic control systems with the desired dynamic properties that are specified by quantized transition functions of finite duration.

Methodology. The theory of transition functions of finite duration is used to set the desired dynamic properties of automatic control systems in discrete time intervals. The modified structural block-diagram symmetry principle provides the formation of accessible desired dynamic characteristics of a closed-loop system with a limited gain factor.

Findings. The method for automatic control system synthesis on the base of discrete time equalizer was developed on condition of full compensation of dynamic properties of the control object and with their partial compensation due to use of modification blocks of reverse structural block-diagram transformation.

Originality. The first proposed mathematical apparatus allows the use of discrete time equalizer as a discrete regulator in automatic control systems. The research on automatic control system synthesis on the base of discrete time equalizer revealed that modified principle of structural block-diagram symmetry should be used for providing the real dynamics of automatic control systems.

Practical value. The results of the research can be used for building the control algorithms for technical objects with their further program implementation in the microcontroller or microprocessor control system.

Keywords: *discrete time equalizer, quantized transition function, transition function of finite duration, modified principle of symmetry*

Introduction. The study [1] proposes to represent the desired transition function of automatic control system as a set of quantized values of the controlled coordinates. The mathematical apparatus developed in [1] can perform an analytical determination of operator images for desired quantized transition functions of finite duration [2], relying only on the values of signal levels at quantization points and a quantization period value. In this approach, the synthesis of automatic control systems is performed without using the standard characteristic polynomials [3].

Thus, avoiding the use of standard characteristic polynomials in the synthesis of automated control systems requires their replacement by other fundamental principles that allow for taking into account the dynamic features of the real technical objects according to the current technological standards of exploitation [4].

The basic fundamental principles that provide synthesis of automatic control systems without using the theory of standard polynomials:

1. The control object should be reduced to one transfer function or, if it is possible, structurally represented as one of the standard forms (the first canonical form of control is the best for this task).

2. The inverse transformation from control object should be performed. The transformation result will be some transfer function or structural block-diagram of an inverse reference (mirrored) model [5]. If the object involves integrators, then their compensation is impractical because presence of integrators increases the astatic order of system.

3. For the practical realization of the structural block-diagram symmetry principle the modification inverse transformation unit should be introduced into the direct branch of a closed-loop system. This unit is an integrating link. Thus, the closed-loop system that consists of control object, mirrored model and modification block will have real and predictable dynamics.

4. On the base of discrete regulator advantages, the desired dynamic of automatic control systems should be specified in the form of a quantized transition function.

5. It is necessary to synthesize a discrete regulator that will provide the technical implementation of the desired quantized transition function.

The study [6] introduces the analogy between setting levels of desired transition function in quantization moments and functioning of frequency equalizer — a device that has a hardware or software implementation and could be widely used for sound signal processing.

In both cases, the level of signal amplification is installed on some local band, but traditional sound equalizer operates in the frequency domain, while setting the levels of desired transition function are realized in the time domain.

Whereas the term "equalizer" commonly means a frequency equalizer, the regulator, which provides the ability to customize the system on the desired quantized transitional functions, was offered to call a discrete time equalizer [6].

In this case, of course, discrete time equalizer is not a hardware component but is a specific program for a microprocessor or microcontroller control system.

Objectives of the article. The synthesis of automatic control systems with discrete time equalizer requires the use of the inverse dynamics problem concept [7] and the principle of structural block-diagrams symmetry with taking into consideration its possible modifications [8].

Let us put the problem of developing the method of closed-loop automatic control system synthesis on the base of discrete time equalizer.

In doing so, the synthesis of discrete time equalizer should be considered for a full compensation of the dynamic object properties and in the case of real (partial) compensation, particularly with using the modified symmetry principle.

Presentation of the main research and explanation of scientific results. In most cases, control object is an analogue, so the systems that include the discrete time equalizer in their structure will be digital-analog. To perform a digital-to-analog conversion in such systems, it is necessary to apply a zero-order holder [9] with transfer function [10]

$$W_{zoh}\left(p\right)=\frac{1-e^{-T_0 p}}{p}=\frac{z-1}{zp}, \qquad (1)$$

where p is the Laplace operator; z is the operator of discrete transformation; T_0 is quantization (sampling) period.

The input signal $x_{inp}(t)$ and the adjustment factors for the discrete time equalizer in the proposed system may be programmed.

When performing the synthesis, the object and its inverse reference model could be described in combination by transfer function $W_r(z)$. A zero-order holder (1) is installed between the discrete time equalizer and transfer function $W_r(z)$.

With full compensation of dynamic properties of the control object using the inverse model, the transfer function $W_r(z)$ is equal to unity

$$W_r(z) = 1.$$

Then the closed-loop system with the discrete time equalizer transfer function $W_{cl}(z)$ will have the following expression

$$W_{cl}\left(z\right)=\frac{W_{eq}\left(z\right)W_r\left(z\right)}{1+W_{eq}\left(z\right)W_r\left(z\right)k_{fb}}=\frac{W_{eq}\left(z\right)}{1+W_{eq}\left(z\right)k_{fb}},$$

where k_{fb} is the feedback factor; $W_{eq}(z)$ is the transfer function of the discrete time equalizer.

The quantized desired form of the transition function is the basis for the implementation of the discrete time equalizer synthesis. According to the research carried out in [1], the discrete time equalizer should be tuned to the discrete transition function of finite duration that is theoretically possible on condition of bringing the characteristic equation to the form of z^n. The desired transfer function of the system in this approach will have the following form

$$W_d\left(z\right)=\frac{a_k z^k+a_{k-1}z^{k-1}+a_{k-2}z^{k-2}+\ldots+a_1 z+a_0}{z^k}, \qquad (2)$$

where k is the order of characteristic equation (should fit or be greater than the order of the characteristic equation of control object); $a_k, a_{k-1}, a_{k-2}, \ldots, a_1, a_0$ are factors that characterize the transition function level increase at each step of quantization.

The transition function that will theoretically be provided in a system with transfer function $W_d(z)$ is shown in Fig. 1 ($t = iT_0$ – quantization time).

The number of levels c_i of transition function $h(iT_0)$ (Fig. 1) is determined by the order of the characteristic equation of desired transfer function by the following formulas [1]

$$\left.\begin{aligned} c_i &= \sum_{j=k-i}^{k} a_j \text{ when } i\le k,\\ c_i &= \sum_{i=0}^{k} a_i \text{ when } i>k. \end{aligned}\right\}. \qquad (3)$$

Herewith, the values of the transition function at the levels will be as follows: $c_0 = a_k$; $c_1 = a_k + a_{k-1}$; $c_2 = a_k + a_{k-1} + a_{k-2}, \ldots$; $c_{k-1}=\sum_{i=1}^{k}a_i$, $c_k=\sum_{i=0}^{k}a_i$. Thus, each level of this function is the sum of the factors a_i, beginning from the factor a_k at the highest degree of the desired polynomial numerator and ending with factor a_0. The steady-state value is the sum of all numerator factors $\sum_{i=0}^{k}a_i$.

The transfer function of the discrete time equalizer $W_{eq}(z)$ is obtained after performing the equation $W_{cl}(z) = W_d(z)$

$$W_{eq}\left(z\right)=\frac{a_k z^k+a_{k-1}z^{k-1}+a_{k-2}z^{k-2}+\ldots+\to}{\left(1-k_{fb}a_k\right)z^k-k_{fb}a_{k-1}z^{k-1}-\to}$$
$$\frac{\to+a_1 z+a_0}{\to-k_{fb}a_{k-2}z^{k-2}-\ldots-k_{fb}a_1 z-k_{fb}a_0}. \qquad (4)$$

The numerator of the received transfer function $W_{eq}(z)$ completely coincides with the numerator of the desired transfer function $W_d(z)$ provided full compensation of control object dynamic properties. As for the denomina-

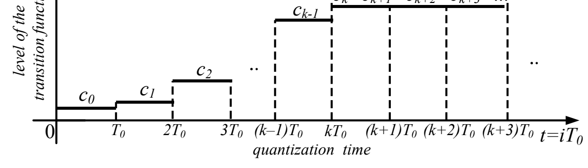

Fig. 1. The transition function of finite duration

tor of the transfer function $W_{eq}(z)$, it is a polynomial of degree k, and the factor at z^k is defined as $(1 - k_{fb}a_k)$.

If the numerator order of the desired transfer function is less than the denominator order, then the relevant factors in the expression (4) will be equal to zero.

In [6] it was found that in closed-loop systems only the use of the modified symmetry principle is of practical importance. The modification block is implemented in the real system. Such an approach gives real dynamics of the closed-loop system instead of the ideal compensation of control object dynamics. Let us perform the discrete time equalizer synthesis for the case of using the modified principle of symmetry with the control object. The functional diagram of the closed-loop system on the base of discrete time equalizer using of the modified structural block-diagram principle includes a block for modification the inverse transformation in its structure (Fig. 2).

The control object represented on this functional diagram (Fig. 2) receives a control signal $u(t)$ and is exposed by several disturbances $f_1(_t)$, $f_2(t), \ldots, f_q(t)$. The feedback sensor for the output coordinate performs the measurement of the coordinate $y(t)$ and turns it into the feedback signal $x_{fb}(t)$.

When using of the modified structural block-diagram symmetry principle, the continuous part of the system consists of the object, its inverse reference model and block for modification of the inverse transformation with the transfer function $W_{\text{mod}}(p) = 1/p$ (Fig. 3). The non-linearity “saturation” can be installed after the block for modification of the inverse transformation to limit the amplitude of control action.

The functioning coordination of the discrete time equalizer with analogue part of the system is performed by using a zero-order holder with the transfer function (1).

All continuous part of the system and zero-order holder, that is “installed” between the discrete time equalizer and continuous part, can be represented as re-

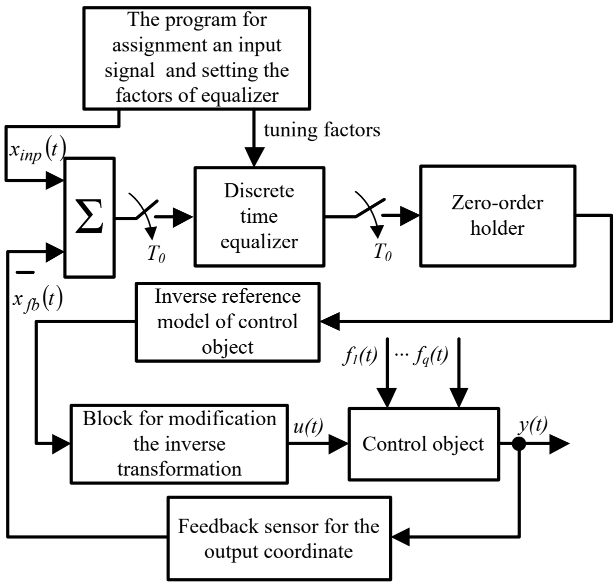

Fig. 2. The functional diagram of the closed-loop system with a discrete time equalizer and a block for modification of the inverse transformation

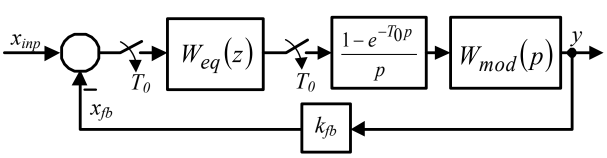

Fig. 3. The structural block-diagram of the closed-loop system with a discrete time equalizer and a block for modification of the inverse transformation

duced transfer function $W_r(z)$. In carrying out Z-transformation, the following expression can be obtained

$$W_r(z) = Z\{W_{\text{mod}}(p)\} = Z\left\{\frac{1}{p}\right\} = \frac{T_0}{z-1}. \quad (5)$$

The formula (5) provides for integration by rectangles, as this would not conflict with the representation of desired transition functions of finite duration, which is also formed by rectangular pulses (Fig. 1). If the input lattice function of the discrete integrator mark the $x(n)$ and as the output – $y(n)$, then the difference equation of integration by the rectangle method will have the following form

$$y(n) = y(n-1) + T_0 x(n-1),$$

where $y(n)$ is the value of the output coordinate at the current quantization moment n; $y(n-1)$ is the value of the output coordinate at the previous quantization moment $(n-1)$; $x(n-1)$ is the value of the input coordinate at the previous quantization moment $(n-1)$.

The numerical integration method of rectangles is illustrated in Fig. 4.

The transfer function of the closed-loop system in discrete form $W_{cl}(z)$ in accordance with Fig. 3 will have the following form

$$W_{cl}(z) = \frac{T_0 W_{eq}(z)}{z + T_0 W_{eq}(z) k_{fb} - 1}. \quad (6)$$

The desired transfer function of the digital-to-analog system can be reduced to discrete form (2). The transfer function of the discrete time equalizer can be obtained by equating the transfer function of the closed-loop system (6) with the desired transfer function

$$W_{eq}(z) = \frac{a_k z^{k+1} + (a_{k-1} - a_k) z^k + \rightarrow}{(T_0 - T_0 k_{fb} a_k) z^k - T_0 k_{fb} a_{k-1} z^{k-1} - \ldots - \rightarrow}$$
$$\frac{\rightarrow + (a_{k-2} - a_{k-1}) z^{k-1} + \ldots + (a_0 - a_1) z - a_0}{\rightarrow - T_0 k_{fb} a_1 z - T_0 k_{fb} a_0}.$$

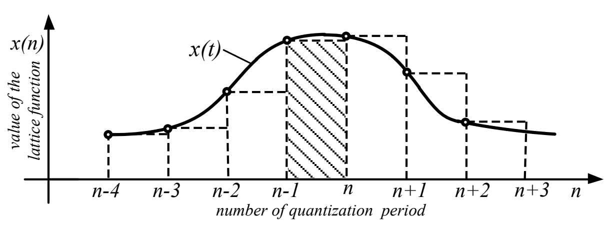

Fig. 4. The numerical integration method of rectangles

The condition of physical implementation of the regulator requires that the order of the numerator of its transfer function should not exceed the denominator order. Thus, the resulting expression for $W_{eq}(z)$ cannot be physically realized, so the order of the numerator $W_{eq}(z)$ should be decreased by one. Then the factor a_k should be equal to zero. The desired transition function in this case will be late for one quantization period (Fig. 5).

The transfer function of the discrete time equalizer, that can be physically realized, will have the following form

$$W_{eq}(z)=\frac{a_{k-1}z^k+\sum_{i=1}^{k-1}\left(a_{i-1}-a_i\right)z^i-a_0}{T_0z^k-T_0k_{fb}\sum_{i=0}^{k-1}a_iz^i}. \tag{7}$$

Thus, the transfer function (7) can be used to determine the parameters of the regulator (discrete time equalizer), which can provide the desired dynamic properties of the automatic control system, given in the form of quantized transition function.

When the control object has the order of aperiodic neutrality $\nu_a > 0$, it is inappropriate to make compensation of its integrative component.

The functional diagram of the closed-loop system on the base of the discrete time equalizer with the presence of the control object with the first order of aperiodic neutrality is shown in Fig. 6.

The reduced transfer function that is necessary for the synthesis of the discrete time equalizer will have the following form

$$W_r(z)=Z\left\{\frac{W_{\text{mod}}(p)}{p}\right\}=Z\left\{\frac{1}{p^2}\right\}=\frac{T_0^2}{\left(z-1\right)^2}.$$

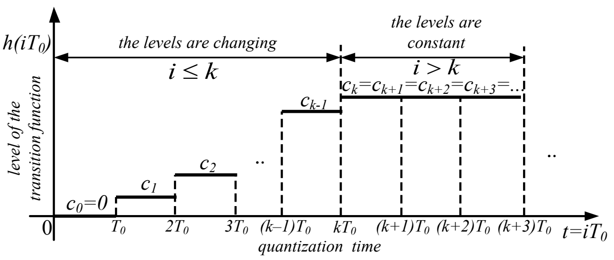

Fig. 5. The transition function of finite duration with a delay of one quantization period

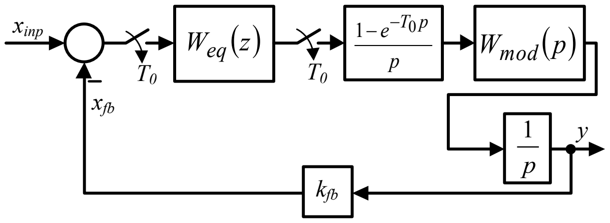

Fig. 6. The structural block-diagram of the closed-loop system with the discrete time equalizer and the first order of control object aperiodic neutrality

The transfer function of the closed-loop system in discrete form $W_{cl}(z)$ in accordance with Fig. 6 will have the following form

$$W_{cl}(z)=\frac{W_{eq}(z)T_0^2}{\left(z-1\right)^2+W_{eq}(z)T_0^2k_{fb}}. \tag{8}$$

Equating the transfer function of the closed-loop system (8) with the desired transfer function (2) gives the transfer function of the discrete time equalizer

$$W_{eq}(z)=\frac{a_kz^{k+2}+\left(a_{k-1}-2a_k\right)z^{k+1}+\rightarrow}{\left(T_0^2-T_0^2k_{fb}a_k\right)z^k-\rightarrow}$$

$$\frac{\rightarrow+\left(a_{k-2}-2a_{k-1}+a_k\right)z^k+\rightarrow}{\rightarrow-T_0^2k_{fb}a_{k-1}z^{k-1}-\rightarrow}$$

$$\frac{\rightarrow+\left(a_{k-3}-2a_{k-2}+a_{k-1}\right)z^{k-1}+\ldots+\rightarrow}{\rightarrow-T_0^2k_{fb}a_{k-2}z^{k-2}-\rightarrow}$$

$$\frac{\rightarrow+\left(a_0-2a_1+a_2\right)z^2+\left(a_1-2a_0\right)z+a_0}{\rightarrow-\ldots-T_0^2k_{fb}a_1z-T_0^2k_{fb}a_0}.$$

For the condition of physical implementation of the regulator in the expression $W_{eq}(z)$ coefficients $a_k = 0$ and $a_{k-1} = 0$ should be accepted. In this case, the desired transition function will have a delay of two quantization periods (Fig. 7).

The expression for the transfer function of the discrete time equalizer for the first order of aperiodic neutrality in the control object will be the following

$$W_{eq}(z)=\frac{1}{T_0^2}\cdot\frac{a_{k-2}z^k+\left(a_{k-3}-2a_{k-2}\right)z^{k-1}+\rightarrow}{z^k-k_{fb}\sum_{i=0}^{k-2}a_iz^i}$$

$$\frac{\rightarrow+\sum_{i=2}^{k-2}\left(a_{i-2}-2a_{i-1}+a_i\right)z^i+\left(a_1-2a_0\right)z+a_0}{}. \tag{9}$$

The transfer function (9) describes the discrete time equalizer, which takes into account the presence of the control object with the first order of aperiodic neutrality. It does not provide any compensatory influence on the integrative component of the control object.

By doing similar calculations, the transfer function for discrete time equalizer at control object with arbitrary aperiodic neutrality can be obtained

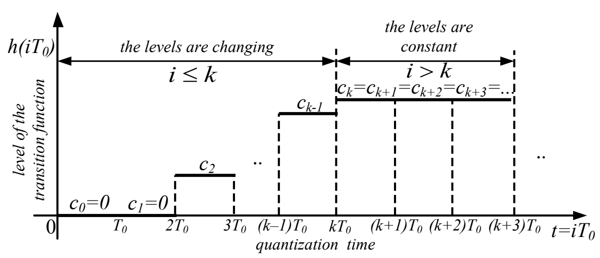

Fig. 7. The transition function of finite duration with a delay of two quantization periods

$$W_{eq}(z)=\frac{1}{T_0^n}\cdot\frac{(z-1)^n\left(a_k z^k+a_{k-1}z^{k-1}+\rightarrow\right.}{z^k-k_{fb}\left(a_k z^k+a_{k-1}z^{k-1}+\rightarrow\right.}$$
$$\frac{\left.\rightarrow+a_{k-2}z^{k-2}+\ldots+a_1 z+a_0\right)}{\left.\rightarrow+a_{k-2}z^{k-2}+\ldots+a_1 z+a_0\right)}. \qquad (10)$$

Let us calculate the order of polynomials of the numerator and denominator in the expression (10). The order of the numerator will be the value of $(n + k)$, and the denominator $-k$. For the condition of physical implementation of the regulator it is necessary that the first n coefficients of the numerator in expression (10) should be equal to zero, that is

$$a_k = a_{k-1} = a_{k-2} = \ldots = a_{k-n+1} = 0.$$

The delay of the desired transient function in this case will be n cycles in accordance with the equations (3).

Thus, formula (10) allows synthesizing the discrete time equalizer using a modified principle of symmetry of structural schemes in any order of aperiodic neutrality of the control object ν_a.

Conclusions:

1. The idea of partitioning the desired transient function into separate parts should be solved in the application not to analog systems with continuous signals, but to discrete systems processing signals in the form of sequences of pulses or digital codes.

2. The analytical synthesis of regulators by the quantized form of the desired transitive function requires the determination of the inverse transformation from the transfer function of the control object that is finding the solution of the inverse dynamics problem from the position of control theory, which leads to the formulation of the principle of structural scheme symmetry [1].

3. The method of automatic control system synthesis allows finding the transfer function of the discrete time equalizer that provides the required dynamic properties of the system, based on the desired transition functions of finite duration.

4. On the basis of the studies the basic mathematical principles for automatic control system synthesis are described based on the discrete time equalizer on condition of full compensation of dynamic properties of the control object and partial compensation – with using the modified principle of structural block-diagram symmetry.

5. The transition function of finite duration and the transfer function of the discrete time equalizer can be interpreted quite simply into the program code to perform the technical implementation by a microprocessor or microcontroller.

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Мета. Розробка методу синтезу систем автоматичного керування з бажаними динамічними властивостями, що задаються за допомогою квантованих перехідних функцій кінцевої тривалості.

Методика. Теорія перехідних функцій кінцевої тривалості використовується для завдання бажаних динамічних властивостей систем автоматичного керування на дискретних часових інтервалах. Модифікований принцип симетрії структурних схем забезпечує формування досяжних бажаних динамічних характеристик замкненої системи за обмеженого значення коефіцієнта підсилення.

Результати. Розроблено метод синтезу систем автоматичного керування на базі дискретного часового еквалайзера за умови повної компенсації динамічних властивостей об'єкта керування та при частковій їх компенсації за рахунок використання блоків модифікації зворотного перетворення структурних схем.

Наукова новизна. Запропонований уперше математичний апарат дозволяє використовувати дискретний часовий еквалайзер в якості дискретного регулятора в системах автоматичного керування. Дослідження особливостей синтезу систем автоматичного керування на базі дискретного часового еквалайзера дозволили встановити, що для забезпечення реальної динаміки цих систем слід використовувати модифікований принцип симетрії структурних схем.

Практична значимість. Результати досліджень можуть бути застосовані для побудування алгоритмів керування технічними об'єктами з подальшою їх програмною реалізацією в мікропроцесорній або мікроконтролерній системі керування.

Ключові слова: *дискретний часовий еквалайзер, квантована перехідна функція, перехідна функція кінцевої тривалості, модифікований принцип симетрії*

Цель. Разработка метода синтеза систем автоматического управления с желаемыми динамическими свойствами, которые задаются с помощью квантованных переходных функций конечной продолжительности.

Методика. Теория переходных функций конечной длительности используется для задания желаемых динамических свойств систем автоматического управления на дискретных временных интервалах. Модифицированный принцип симметрии структурных схем обеспечивает формирование достижимых желаемых динамических характеристик замкнутой системы при ограниченном значении коэффициента усиления.

Результаты. Разработан метод синтеза систем автоматического управления на базе дискретного временного эквалайзера при полной компенсации динамических свойств объекта управления и при частичной их компенсации за счет использования блоков модификации обратного преобразования структурных схем.

Научная новизна. Предложенный впервые математический аппарат позволяет использовать дискретный временной эквалайзер в качестве дискретного регулятора в системах автоматического управления. Исследования особенностей синтеза систем автоматического управления на базе дискретного временного эквалайзера позволили установить, что для обеспечения реальной динамики этих систем следует использовать модифицированный принцип симметрии структурных схем.

Практическая значимость. Результаты исследований могут быть использованы для построения алгоритмов управления техническими объектами с последующей их программной реализацией в микропроцессорной или микроконтроллерной системе управления.

Ключевые слова: *дискретный временной эквалайзер, квантованная переходная функция, переходная функция конечной длительности, модифицированный принцип симметрии*

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ANALYTICAL METHODS FOR DESIGNING TECHNOLOGICAL TRAJECTORIES OF THE OBJECT OF LABOUR IN A PHASE SPACE OF STATES

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АНАЛІТИЧНІ МЕТОДИ ПРОЕКТУВАННЯ ТЕХНОЛОГІЧНИХ ТРАЄКТОРІЙ ПРЕДМЕТІВ ПРАЦІ У ФАЗОВОМУ ПРОСТОРІ СТАНІВ

Purpose. The development of analytical methods for designing technological motion trajectories of objects of labour in the state space with the purpose of construction of closed PDE-models, used to describe the manufacturing system.

Methodology. For derivation of an equation of the labour object movement in the phase space of states, there has been applied a mathematical tool and the variational calculation methods of analytical mechanics.

Findings. An equation of labour object movement in the state of space has been derived and motion integrals, related to the uniformity of time and state space have been considered.

Originality. PDE-models of manufacturing systems, used for the engineering of the high performance manufacturing control systems have been improved. The offered model of technological resources transfer to the object of labour is based not on the traditional phenomenological description of the static production phenomena, but on conservation laws, which characterize the transfer process of technological resources to the object of labour and