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Extending the Method for Development of Double-Loop Continuous Tracking Systems to Discrete Equivalents

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Solutions to increase the accuracy of radio systems are analyzed. It is shown that invariance in a single-loop automatic control system affects its stability. Article [13] offers to apply a method for the synthesis of continuous high precision double-loop automatic control systems which are equivalent to combined systems in conditions when some values (entry useful action) can't be measured for development of tracking systems (in particular, radio systems, where the entry useful action can't be measured, and therefore combined control is impossible). The article considers extension of the method for the synthesis of double-loop automatic control systems to discrete systems equivalent to combined systems in an environment with simultaneous entry useful (preset) action and external disturbances and interferences. The developed method makes it possible to synthesize discrete high-precision automatic control tracking systems equivalent to combined ones in an environment with a controlled variable (entry useful action) which cannot be measured. A discrete transfer function from an error in double-loop system (5), an invariance condition (6), and a characteristic equation (8) are obtained. In this case, the numerator polynomial of the transfer function from error must have a difference of polynomials. The article demonstrates that invariance conditions (improved accuracy) can be achieved without any destabilization in the first loop. In this discrete tracking system equivalence to combined systems is achieved by two control loops and not by three loops as in the differential coupling method. A double-loop discrete automatic control system equivalent to a combined system was synthesized. A stochastic regulator was calculated and made, and the influence of this regulator on the astatism of the system (that is, on its accuracy) was analyzed. The proposed method can be used to develop discrete tracking systems (especially radio systems, where entry useful action cannot be measured due to interference), and it can be applied for laser radar tracking systems, and control systems for aircraft of various purposes.

Keywords: radio tracking systems; high accuracy; method of synthesis; discrete automatic control systems; defect of the transfer function; invariance; stability; control device; control object; electric drive; antenna system; loop; regulator

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Introduction

Higher accuracy of radio systems is one of the basic requirements in the course of their development. A number of works [1–3, 5, 7, 11–14, 16, 18–30] consider how to achieve invariance (high accuracy) without compromising the stability of automatic control systems.

Adaptive neural tracking control for a class of output feedback nonlinear systems that do not switch in the feedback structure with an average delay time was studied in [23, 24].

Adaptive learning strategies for neural networks based on consensus control strategies were proposed in [25].

Adaptive control requires a measurable entry action, which is quite often hard to implement. Where the entry action cannot be measured (unknown), adaptive algorithms are not always appropriate.

In parallel with continuous-time radio systems, discrete-time automatic control systems are widespread [3, 4]. These include radio and laser systems, which determine coordinates of aircraft, airplanes, sea and river vessels, inertial coordinate determining systems for mobile objects [9].

Such tasks are best solved with the help of combined automatic systems that use the principles of control from error and from preset action if there are any interference [4, 16, 26–30].

The works [4, 5] considered a combined control method subject to the condition that preset action was measured directly.

In practice, however, this condition is seldom fulfilled. For example, this is the case with all radar tracking systems in which it is impossible to measure directly motion parameters (preset action) of the tracked object, or with missile control systems that are subject to various kinds of disturbances.

In this situation, it is necessary to use a method for synthesizing high-precision automatic control tracking systems equivalent to combined ones subject to simultaneous entry useful (preset) action X and external disturbances and interferences [13, 14].

1 Problem statement

Well-known is a single–loop continuous radio system [3, 4] (Fig. 1), where CO is a control object, and CD is a control device.

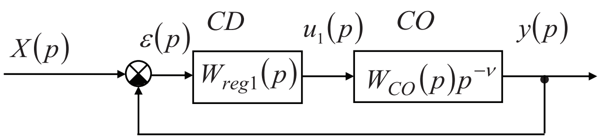

Fig. 1. Single-loop automatic control radio system

We obtain the conditions for achieving invariance in a single-loop automatic control system, for which we determine a transfer function from control error:

$$W_\varepsilon(p) = \frac{1}{1 + W_p(p)}, \quad (1)$$

$$W_p(p) = W_{reg1}(p)\, W_{CO}(p)\, p^{-\nu}, \quad (2)$$

where $W_{reg1}(p)$ is the transfer function of regulator 1; $W_{CO}(p)$ is the transfer function of the control object without integrating links; ν is the astatism order.

Accordingly

$$W_{reg1}(p) = \frac{B_{reg1}(p)}{C_{reg1}(p)}; \;\; W_{CO}(p) = \frac{M(p)}{N(p)},$$

where $B_{reg1}(p)$, $C_{reg1}(p)$ are the polynomials of the transfer function of controller 1; $M(p)$, $N(p)$ are the polynomials of the transfer function of the control object without integrating links.

The transfer function of an open loop is represented by the expression (2). We substitute (2) for (1), having previously expressed the corresponding transfer functions in terms of their polynomials, then

$$W_\varepsilon(p) = \frac{1}{1 + \frac{B_{reg1}(p)\, M(p) p^{-\nu}}{C_{reg1}(p)\, N(p)}} =$$

$$= \frac{C_{reg1}(p)\; N(p)}{C_{reg1}(p)\; N(p) + B_{reg1}(p)\; M(p)\; p^{-\nu}}.$$

Then the invariance condition will be as follows

$$C_{reg1}(p)\; N(p) = 0, \quad (3)$$

the characteristic equation

$$C_{reg1}(p)\; N(p) + B_{reg1}(p)\; M(p)\; p^{-\nu} = 0. \quad (4)$$

The analysis of expressions (3) and (4) shows that the invariance condition is included in the characteristic equation, therefore, the achievement of the invariance conditions is associated with a change in the characteristic equation, i.e. with a change in the roots on the complex plane p. Hence it follows that invariance cannot be achieved without stability upset in a single-loop continuous radio system.

It was shown in [13, 14] that it is possible to achieve invariance avoiding instability in continuous double-loop radio systems. The article proposes a method for synthesis of continuous high precision double-loop automatic control systems which are equivalent to combined systems, in conditions when some values cannot be measured (entry useful action) in order to develop tracking systems (in particular, radio systems, where the entry useful action cannot be measured, and therefore combined control is impossible).

However, it did not consider using the above method for widely used discrete radio systems, which issue deserves attention and seems relevant.

2 Analysis of recent research and publications

There are quite a lot of works by national scholars on methods of synthesis of combined automatic control system regulators with their location in open channels (in connection with set actions and disturbing effects).

Methods of synthesis of regulators for compensation of external disturbances from the conditions for achieving error invariance with respect to these effects for combined automatic control systems, as well as for systems equivalent to combined automatic systems, were considered by E. J. Davison, H. F. Zaitsev [4, 13].

A number of works, e.g. [1–3, 5, 7, 13, 14, 18–30] consider how to achieve invariance (high accuracy) of automatic control systems without compromising their stability.

Such tasks are best solved by combined systems (combined control method), that use the principles of control from error and from preset (disturbing) action [1, 2, 4].

In conditions where external influences (preset action and disturbing effects) cannot be measured (combined control is impossible), a method for synthesis of continuous high precision double-loop automatic control systems equivalent to combined ones [3, 4, 6] is suggested.

Research [7, 14] demonstrate that invariance cannot be achieved in a single-loop automatic control system without compromising its stability.

In adaptive systems (adaptive control method), adaptive control requires a measurable entry action, which is quite often hard to get. Where the entry action cannot be measured (unknown), adaptive algorithms are not always appropriate [18–20].

To solve this problem, the differential coupling method can be used. It is important to note, that unlike the differential coupling method, equivalence to combined systems in the suggested apparatus for construction of a tracking system is achieved by two control loops and not by three loops. A double-loop automatic control system is equivalent to a combined one, since it ensures: invariance of the error with respect to preset action without measuring it directly; stability of the first loop with a stable second loop [13, 14].

The purpose of the article is to use the method of synthesis of high accuracy continuous tracking automatic control systems equivalent to combined ones with a controlled variable (entry useful action) which cannot be measured for discrete tracking systems (in particular, radio systems, where the entry useful action cannot be measured, and therefore combined control is impossible).

3 Statement of materials

Description of the method. Let's assume that the operator p (formally, without taking into account the connection $z = \exp(pT)$, where T is the discreteness period) can be replaced with a discrete operator z [3, 9, 12] while preserving all previously introduced transfer functions and polynomials [13, 14].

The only exception will be made to designate ν (the order of astatism of the control object), instead of which the defect d of the control object transfer function is to be understood. The diagram of the open second loop will be as shown in Fig. 2.

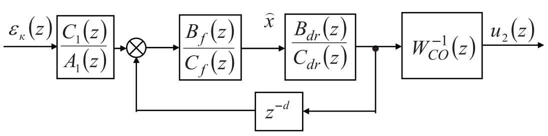

Fig. 2. Block diagram of the open second loop in discrete time

It can be seen from the analysis of Fig. 2 that structurally, the second loop of a discrete automatic control system is the product of the inverse discrete transfer function from error in the first loop to the discrete transfer function of a stochastic controller covered by positive feedback with a delay operator to a power $-d$, as well as to the inverse transfer function of the control object without the delay operator.

Using a double-loop continuous automatic control system [13, 14], it is possible to make a diagram of a double-loop system equivalent to a combined one (Fig. 3) in discrete time.

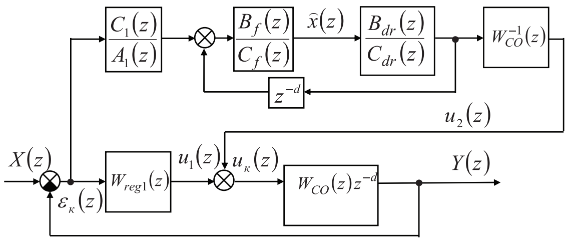

Fig. 3. Block diagram of a double-loop system equivalent to a combined one in discrete time

By analogy with [13, 14], the discrete transfer function from the error in a double-loop system can be found using the formula:

$$W_\varepsilon^{(2)}(z) = \frac{A_\kappa(z)}{C_\kappa(z)} = \frac{A_\kappa(z)}{C_1(z)\ C_{reg2}(z)}, \quad (5)$$

where the invariance condition

$$A_\kappa(z) = A_1(z)\left[C_{reg2}(z) - B_{reg2}(z)\ z^{-d}\right] = 0; \quad (6)$$

the characteristic equation

$$C_1(z)\ C_{reg2}(z) = 0. \quad (7)$$

From the analysis of equations (6) and (7), as well as from the analysis of equations in [13, 14], it follows that the achievement of invariance conditions occurs without violating the stability in the first loop.

Since the stochastic regulator is a sequential connection of an optimal filter with a discrete transfer function $B_f(z)/C_f(z)$ and a deterministic regulator with a discrete transfer function $B_{dr}(z)/C_{dr}(z)$, the characteristic equation (7) should be specified as follows:

$$C_1(z)\ C_f(z)\ C_{dr}(z) = 0, \quad (8)$$

where all the polynomials: $C_1(z)$, as well as $C_f(z)$ and $C_{dr}(z)$ are stable, i.e. the characteristic equations $C_f(z) = 0$ and $C_{dr}(z) = 0$ do not have any roots in a unit circle on the complex plane z.

4 Method Study. Synthesis of discrete automatic control systems

Let's study the tracking system development methodology and synthesize discrete systems.

We will consider some special cases arising from the methodology of development of discrete automatic control systems equivalent to combined ones.

Let the difference of the polynomials in the discrete transfer function numerator of the double-loop system which is equivalent to a combined system be as follows

$$C_{reg2}(z) - B_{reg2}(z) = 0, \quad d = 0. \quad (9)$$

Then the error is

$$\varepsilon_\kappa(z) = W_\varepsilon^{(2)}(z)\ X(z) = \frac{A_\kappa(z)}{C_\kappa(z)} X(z) = 0.$$

The diagram in Fig. 2 for the discrete second loop will be as shown in Fig. 4.

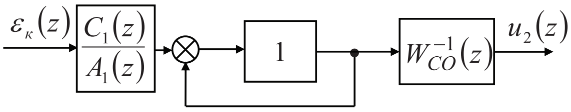

Fig. 4. Open discrete second loop diagram

The coefficient of a link with gain 1 covered by positive feedback is equal to infinity. Therefore, in order to achieve invariance (6), there must be an amplifier with an infinitely large gain in the second loop (as it is for continuous systems in a similar situation).

Let the difference of the polynomials in the discrete transfer function numerator of the double-loop system which is equivalent to a combined system be as follows

$$C_{reg2}(z) - B_{reg2}(z) = 1 - z^{-1},\ d = 0. \qquad (10)$$

The expression $(1 - z^{-1})$ is equivalent to the operator p (equivalent to the derivative).

This means that astatism of the entire system increases by one. This is possible if $C_{reg2}(z) = 1$, and $B_{reg2}(z) = z^{-1}$ (Fig. 5).

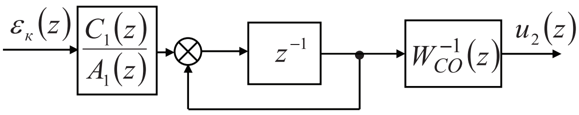

Fig. 5. Discrete second loop diagram

In this case, the characteristic equation (7) is determined only by polynomial $C_1(z)$.

Let the difference of the polynomials in the discrete transfer function numerator of the double-loop system which is equivalent to a combined system be as follows

$$C_{reg2}(z) - B_{reg2}(z)\ z^{-1} = \left(1 - z^{-1}\right)^2,\quad d = 1. \qquad (11)$$

The expression $\left(1 - z^{-1}\right)^2$ is equivalent to the second derivative, which leads to an increase in astatism by two orders of magnitude. Such an astatism increase is possible if $C_{reg2}(z) = 1 - 2z^{-1}$, and $B_{reg2}(z) = z^{-1}$.

However, in this case, the characteristic equation of the type 2 regulator $C_{reg2}(z) = 0$ has root $z_1 = 2$ that goes beyond the unit circle (it means that a discrete automatic control system is unstable).

Therefore, taking into account stability and astatism increase by two orders of magnitude, it is necessary to write polynomials of regulator 2 differently, i.e. $C_{reg2}(z) = 1 - 0,5z^{-1}$, $B_{reg2}(z) = 1,5 - z^{-1}$ (Fig. 6).

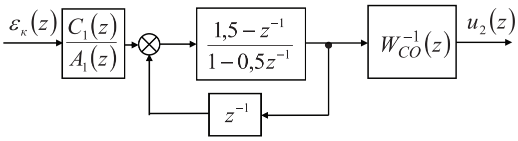

Fig. 6. Open discrete second loop diagram

5 Results

As a result, a double-loop discrete automatic control system was synthesized. A stochastic regulator was calculated and made, and the influence of this regulator on the astatism of the system (that is, on its accuracy) was analyzed.

Polynomials $B_{reg2}(z)$, $C_{reg2}(z)$ with different values of the first loop astatism are shown in Table 1.

Tabl. 1 Polynomials of the stochastic regulator transfer function

d	0	1
$B_{reg2}(z)$	z^{-1}	$1,5 - z^{-1}$
$C_{reg2}(z)$	1	$1 - 0,5z^{-1}$
$C_{reg2}(z) - B_{reg2}(z)\ z^{-d}$	$1 - z^{-1}$	$\left(1 - z^{-1}\right)^2$

A comparative assessment of the effectiveness of the synthesized double-loop system and a target one [13,14] was carried out using an analytical method and a method of mathematical modeling.

A comparative analysis of the effectiveness of the synthesized double-loop system and the existing one was done using the analytical method [14, 23] and the method of mathematical modeling with a single speed drop (speed jump) at the input. Figure 7 shows diagrams of transitional processes: 1 – for the existing system; 2 – for the system synthesized by this method.

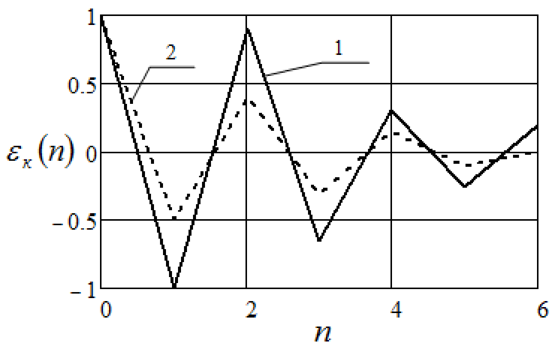

Fig. 7. Diagrams of transitional processes

A comparative analysis shows that under the same working conditions, the quality indicators of the transitional process are higher for the synthesized system.

The research results regarding tracking systems with various stochastic control regulators have shown their high efficiency.

When a synthesized double-loop automatic control system is used, the accuracy of tracking, especially as concerns maneuvering objects (targets), also increases and therefore the possibility of tracking disruption decreases.

Conclusions

1. The method for synthesis of continuous double-loop automatic control systems [13] was extended to discrete systems equivalent to combined systems in the environment with simultaneous entry useful (preset) action and external disturbances and interferences.

2. The developed method makes it possible to synthesize discrete high-precision automatic control tracking systems equivalent to combined ones in conditions with a controlled variable (entry useful action) which cannot be measured.

3. In this discrete tracking system, equivalence to combined systems is achieved by two control loops and not by three loops as in the differential coupling method.

4. A double-loop discrete automatic control system equivalent to a combined system was synthesized. A stochastic regulator was calculated and made, and the influence of this regulator on the astatism of the system (that is, on its accuracy) was analyzed.

5. The proposed method is advised for development of discrete tracking systems based on angular coordinates (in particular, radio systems, where the entry useful action cannot be measured, and therefore combined control is impossible), as well as for stabilization systems and control systems for aircraft of various purposes.

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Поширення методу побудови двоконтурних безперервних слідкуючих систем на дискретні відповідники

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Проведено аналіз розв'язання задачі підвищення точності радіотехнічних систем. Показано, що в одноконтурній радіотехнічній системі не можна досягти інваріантності без зміни стійкості.

У [13] запропоновано метод синтезу слідкувальних безперервних двоконтурних систем автоматичного управління високої точності, еквівалентних комбінованим, в умовах величини, яка не вимірюється (вхідного корисного впливу) для побудови слідкувальних систем (особливо радіотехнічних, де вхідний корисний вплив не вимірюється, а тому і комбіноване управління неможливе).

Розглянуто узагальнення методу синтезу безперервних двоконтурних систем на дискретні системи, еквівалентні комбінованим, в умовах наявності одночасно як вхідного (задавального) впливу, так і зовнішніх впливів і перешкод.

Розроблений метод дозволяє синтезувати дискретні слідкувальні системи автоматичного управління високої точності, еквівалентні комбінованим, в умовах керованої величини, яка не вимірюється (вхідної корисної дії). Отримано дискретну передаточну функцію за помилкою двоконтурної системи (5), умову інваріантності (6), характеристичне рівняння (8). При цьому поліном чисельника передаточної функції за помилкою повинен мати різницю поліномів.

Показано, що умова інваріантності (підвищення точності) відбувається без порушення стійкості першого контуру. При даній побудові дискретної слідкувальної системи еквівалентність комбінованим системам, на відміну від методу диференціальних зв'язків, досягається не трьома, а двома контурами управління.

Синтезовано двоконтурну дискретну систему автоматичного управління, еквівалентну комбінованій. Розраховано і побудовано стохастичний регулятор, проведено аналіз впливу цього регулятора на астатизм системи (тобто її точність).

Запропонований метод доцільно застосовувати для побудови дискретних слідкувальних систем (особливо радіотехнічних, де вхідний корисний вплив не вимірюється за наявності перешкод), а також в лазерних радіолокаційних слідкувальних системах, системах управління літальними апаратами різного призначення.

Ключові слова: радіотехнічні слідкувальні системи; висока точність; метод синтезу; дискретні системи автоматичного управління; дефект передаточної функції; іваріантність; стійкість; пристрій управління; об'єкт управління; електропривод; антенна система; контур; регулятор