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STRUCTURALLY PARAMETRIC IDENTIFICATION OF OBJECT DESCRETE MODELS WITH DELAY FOR TUNING SMITH CONTROLLERS

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Construction of Smith digital controller on the basis of equivalence principle of dynamic object models with delay has been suggested.

Synthesis of control systems starts, as a rule, with object model determination. In practice, information about object is obtained in the form of inputs and outputs available for direct measurement. Actually, impact reaction time delay τ typical for heat-and-power engineering, chemical, metallurgical processes is always observed in objects. It is known that delay adversely affects stability, accuracy and quality of closed system [1]. There are many ways for solving this problem. The most widespread method is the use of delay compensation methods (for example, Smith, Reswick controllers etc.) [2]. These controllers had significant disadvantage from the point of view of delay element practical realization at analog engineering [3]. Realization of such element the delay time of which could be changed in wide range is rather difficult. Digital technique development allowed solving the given problem. However, in both cases, it is necessary to know rather exactly the mathematical model of object inertial part which does not contain delay and it is necessary to know exactly delay value as well [3].

The methods of parametric identification based on the fact that the accepted model should approximate well the experimental data became the most widespread. Accuracy of reclaimed delay value is determined to a large extent by correspondence of mathematical model to the object and namely its inertial part which does not contain delay. Delay time differs significantly from actual one at model structural deviations. Using such models for Smith type controllers does not result in desired results.

Mathematical models in which input action equality involves response reaction equality are called equivalent ones in paper [4]. It is stated in paper [5] that it is possible to say about strict equivalence at coincidence of object and model dynamic properties. The modified method of V. Viskovatov of structurally parametric identification suggested in [6] and based on continued fraction theory allows constructing discrete model strictly equivalent to continuous object.

The matter of the method is in the fact that calculated identifying matrix is formed on the basis of discrete in-output data. The first two lines of this matrix form consecutive measurements of input and output variables and the rest elements are calculated by recurrence relation until a line with null elements appears. The first column till a null line determines structure and values of parameters of discrete transfer function (DTF). And if in the second line in object reaction measurements (in deviations) the first k elements are null ones then the line shifts by k elements to the left. This shift determines delay in discrete representation with accuracy up to sampling increment parameter. Object DTF is obtained in the form:

$$G(z)=\frac{b_0+b_1z^{-1}+\ldots+b_nz^{-n}}{1+a_1z^{-1}+\ldots+a_nz^{-n}}z^{-d}=\frac{P_n(z)}{Q_n(z)}z^{-d}, \quad (1)$$

where n is the order of the model determined by matrix dimension and d determines delay by time $d\Delta t$. The obtained model (1) possesses the same dynamic properties as continuous object as one-to-one correspondence is determined between nulls and poles, continuous object $G(s)$ and discrete model with consistent Z-conversion $z=e^{s\Delta t}$. The carried out numerous model researches for objects: aperiodic, stable and unstable, nonminimum-phase etc. confirmed entirely the validity of reduced continuous transfer functions of inertial part of linear dynamic objects. The researches showed that the equivalence between continuous objects and discrete models is implemented at sampling increment Δ selection from epoch range ($\Delta t_{\min}$, $\Delta t_{\max}$) [6].

Strict equivalence results in the following structure chart of Smith compensator (Fig. 1). Here $G_0(s)$ is the transfer function of the object without delay, $e^{-\tau s}$ is the transfer function of delay unit, $G_0^{м}(z)$ is the discrete transfer function of the object without delay, z^{-d} is the discrete transfer function of delay unit, $R(z)$ is the digital controller, y is the output signal of the object, x is the desired behavior of the object, u is the control object.

Such system may be realized only in the case when delay time τ of control object is multiple to sampling increment Δt.

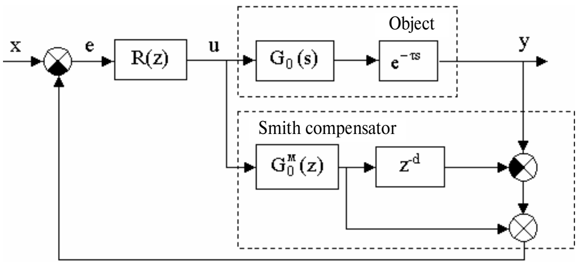

Fig. 1. *Smith compensator in digital system*

DTF $G(z)$ of the object with a certain sampling increment Δt is reduced at the first stage by known in-output variables by modified algorithm of V. Viskovatov. As interval ($\Delta t_{\min}$, $\Delta t_{\max}$) is known beforehand it is necessary to work out the criterion allowing us to state that the reduced DTF $G(z)$ is equivalent to the object.

It is shown in paper [6] that selecting Δt from the range ($\Delta t_{\min}$, $\Delta t_{\max}$) the null and pole images in s-plane obtained by Z-reconversion $s=\dfrac{\ln(z)}{\Delta t}$, remained stationary. Taking into account this fact the following algorithm of determining DTF $G(z)$ equivalent to the continuous object may be proposed:

1) identification algorithm includes in-output information with a certain sampling increment Δt;
2) DTF $G^k(z)$ is reduced for increment $k\Delta t$ (for a start $k=1$) by modified algorithm of V. Viskovatov;
3) using the same algorithm DTF $G^{k+1}(z)$ for increment $(k+1)\Delta t$ is reduced;
4) if orders of DTF $G^k(z)$ and $G^{k+1}(z)$ as well as images of nulls and poles in s-plane coincide then it is possible to state that $G^k(z)$ and $G^{k+1}(z)$ are equivalent to continuous object and $k\Delta t \in (\Delta t_{\min}, \Delta t_{\max})$, $(k+1)\Delta t \in (\Delta t_{\min}, \Delta t_{\max})$. Otherwise, it is necessary to increase k by a unity and return to pt. 3.

Thus, variation of sampling increment Δt allows retrieving additional information about the object with the help of which the fact of obtained model equivalence is established.

For objects with delay there is their own specification connected with the fact that delay time τ is reduced only in the case when it is multiple to sampling increment Δt. In the case if delay time τ is not multiple to sampling increment Δt it may be presented in the form of $\tau=d\Delta t+\mathrm{d}\Delta\tau$, where $d=[\tau/\Delta t]$. Discrete transfer function of the object $G(z)$ identifies exactly only a part of delay, equal to $d\Delta t$, that is the transfer function contains a multiplier z^{-d}. The rest part of $\Delta\tau$ influences the properties of digital control system as the information about $\Delta\tau$ is lost.

Principle of sampling increment variation allows selecting Δt in the range ($\Delta t_{\min}$, $\Delta t_{\max}$) so that it is multiple to τ (on condition that $\tau \geq \Delta t_{\min}$). Thus, two problems appear: 1) to estimate delay time τ provided that object DTF is known; 2) to determine interval ($\Delta t_{\min}$, $\Delta t_{\max}$).

To determine delay time with prescribed accuracy the approach based on the following sequence of operations was theoretically justified:

1) continuous transfer function (CTF) $G(s)$ is reduced identically by DTF $G(z)$. The continuous object reaction is determined in the form of analytical dependence with known input action by CTF;
2) the reverse tabulation of the obtained dependence, at which an argument value corresponding to null reaction magnitude is determined, is fulfilled starting with the first null value of object reaction; knowing the time of input action start and the obtained time value the delay time is determined with accuracy defined by tabulation accuracy.

To determine $\Delta t_{\max}$ solving the problem of structurally parametric identification in paper [6] the condition of SP-identifiability was stated: If it is supposed that besides actual nulls and poles there are pairs of complex-conjugate nulls and poles of continuous transfer function $s_1^{н},s_2^{н},\ldots,s_m^{н}$, $s_1^{п},s_2^{п},\ldots,s_n^{п}$ respectively, then imaginary parts of specified singular points should satisfy the condition of SP-identifiability in the following form:

$$\Delta t \cdot \max\left|\mathrm{Im}[s_1^{н}, s_2^{н},\ldots, s_m^{н}, s_1^{п}, s_2^{п},\ldots, s_n^{п}]\right| < \pi,$$

where Δt is the value of sampling increment. However, if all singular points are real the condition of SP-identifiability can not be used. In this case the search method should be used to determine $\Delta t_{\min}$ and $\Delta t_{\max}$: taking a certain sampling increment as the initial one, to decrease (increase) step-by-step its value while all singular points keep their position (with specified accuracy).

Sampling increment search is inefficient in automatic control systems as it results in excess loading of computing machinery. Therefore, to estimate this range the **statement** is proved: if the object has real nulls $s_1^{н},s_2^{н},\ldots,s_m^{н}$ and poles $s_1^{п},s_2^{п},\ldots,s_n^{п}$, then to select the sampling increment $\Delta t \in (\Delta t_{\min}, \Delta t_{\max})$, allowing constructing its discrete model by modified algorithm of V. Viskovatov the following ratios are valid:

$$\Delta t_{\min} = -\frac{\ln(1-\varepsilon)}{\left|\max(s_1^{н}, s_2^{н},\ldots, s_m^{н}, s_1^{п}, s_2^{п},\ldots, s_n^{п})\right|}, \qquad (2)$$

$$\Delta t_{\max} = -\frac{\ln(\varepsilon)}{\left|\min(s_1^{\text{н}}, s_2^{\text{н}}, ..., s_m^{\text{н}}, s_1^{\text{п}}, s_2^{\text{п}}, ..., s_n^{\text{п}})\right|}, \quad (3)$$

where ε is a certain specified value, arbitrarily small (and ε>0).

Values of nulls $s_1^{\text{н}}, s_2^{\text{н}}, ..., s_m^{\text{н}}$ and poles $s_1^{\text{п}}, s_2^{\text{п}}, ..., s_n^{\text{п}}$ are determined at the stage of constructing equivalent DTF. The value ε is specified depending on accuracy of calculations.

Thus, the developed approach reduces DTF equivalent to control object, determines delay time with specified accuracy and allows selecting sampling increment multiple to delay time. Therefore, the suggested algorithm allows using Smith controllers (as well as Vatanabe Solodovnikov ones etc.) for synthesizing digital control systems by object with delay.

Example.

Let us consider aperiodic object of the second order with CTF of the form:

$$G(s) = \frac{1}{(3s+1)(5s+1)} e^{-5,2s}. \quad (4)$$

Object transfer characteristic is described by time function:

$$y(t) = \begin{cases} 0, & t < \tau, \\ 1 + 1,5e^{-\frac{t-\tau}{3}} - 2,5e^{-\frac{t-\tau}{5}}, & t \geq \tau. \end{cases}$$

Let us sample function $y(t)$ with an increment τ=1 s. Let us suppose that values of output variable at moments which are initial information for control system synthesis are measured: $y(0)=0$; $y(1)=0$; $y(2)=0$; $y(3)=0$; $y(4)=0$; $y(5)=0$; $y(6)=0,018533$; $y(7)=0,079027$; $y(8)=0,161838$; $y(9)=0,253488$; $y(10)=0,345613$; $y(11)=0,433282$; $y(12)=0,513834$; $y(13)=0,58607$; $y(14)=0,649717$; ...

According to modified algorithm of V. Viskovatov [6] elements of the second line of identifying matrix are shifted to the first null element and it takes a form corresponding to Table 1.

Table 1. *Identifying matrix for Δt=1 s*

1	1	1	1	1	1	1
0,018533	0,079027	0,161838	0,253488	0,345613	0,433282	0,513834
−3,2641	−7,73243	−12,6776	−17,6485	−22,3789	−26,7225	~
1,89516	4,84848	8,27077	11,7924	15,19126	~	~
−0,189417	−0,480204	−0,815527	−1,159731	~	~	~
0,0231802	0,0586956	0,099367	~	~	~	~
0	0	~	~	~	~	~

As nulls appear in the seventh line, matrix computing is stopped and continued fraction is formed from the elements of the first column

$$G(z) = \cfrac{0,018533z^{-6}}{1 + \cfrac{-3,2641z^{-1}}{1 + \cfrac{1,89516z^{-1}}{1 + \cfrac{-0,189417z^{-1}}{1 + 0,231802z^{-1}}}}}.$$

Reducing this fraction we obtain DTF of the following form:

$$G(z) = \frac{0,018533z^{-1} + 0,03204z^{-2} + 0,000811z^{-3}}{1 - 1,535262\, z^{-1} + 0,586646z^{-2}} z^{-5}. \quad (5)$$

Let us note that in numerator (5) multiplier z^{-1} supports the condition of process physical performability. This model has two poles: $z_1^{\text{п}}=0,716532$; $z_2^{\text{п}}=0,81873$ and two nulls: $z_1^{\text{н}}=-1,703154$; $z_2^{\text{н}}=-0,02568$. According to one-to-one mapping in s-plane we have poles $s_1^{\text{п}}=-0,333332$, $s_2^{\text{п}}=-0,2$ and as $z_1^{\text{н}}<0$, $z_2^{\text{н}}<0$ then according to investigations carried out in paper [6] there are no these nulls in CTF. Delay time in this case takes the value

$$\tau = d \cdot \Delta t = 5 \cdot 1 = 5 \text{ s}.$$

To check out equivalence of the obtained DTF to the object let us sample function $y(t)$ with increment Δt=2 s. Values of output variable at time moments have the form: $y(0)=0$; $y(2)=0$; $y(4)=0$; $y(6)=0,018533$; $y(8)=0,161838$; $y(10)=0,345613$; $y(12)=0,513834$; $y(14)=0,649717$; $y(16)=0,752673$; $y(18)=0,827781$; ...

According to the modified algorithm of V. Viskovatov [6] elements of the second line of identifying matrix are shifted to the first null element and it takes the form of Table 2.

Table 2. *Identifying matrix for Δt=2 s*

1	1	1	1	1	1	1
0,018533	0,161838	0,345613	0,513834	0,649717	0,752673	0,827781
−7,732429	−17,64846	−26,725289	−34,05723	−39,6125	−43,6652	~
6,450034	15,192199	23,320822	29,93433	34,96548	~	~
−0,072972	−0,159352	−0,236489	−0,298072	~	~	~
0,17163	0,374795	0,556222	~	~	~	~
0	0	~	~	~	~	~

As there are nulls in the seventh line matrix computing is stopped and continued fraction is formed from the first column elements.

$$G(z) = \cfrac{0,018533z^{-3}}{1 + \cfrac{-7,732429z^{-1}}{1 + \cfrac{6,450034z^{-1}}{1 + \cfrac{-0,072972z^{-1}}{1 + 0,17163z^{-1}}}}},$$

Reducing this fraction we obtain DTF of the following form:

$$G(z) = \frac{0,018533z^{-1} + 0,121367z^{-2} + 0,020516z^{-3}}{1 - 1,183737\, z^{-1} + 0,344154z^{-2}} z^{-2}. (6)$$

The given object has two poles $z_1^{\text{п}}=0,7513417$; $z_2^{\text{п}}=0,67032$ and two nulls $z_1^{\text{н}}=-6,37503$; $z_2^{\text{н}}=-173649$. According to one-to-one mapping in s-plane we have poles $s_1^{\text{п}}=-0,333332$, $s_2^{\text{п}}=-0,2$; and as $z_1^{\text{н}}<0$, $z_2^{\text{н}}<0$ then there are no these nulls in DTF. Delay time in this case has value $\tau = d \cdot \Delta t = 2 \cdot 2 = 4$ s.

As it is seen, for Δt=1 s and Δt=2 s DTF (5), (6), images of nulls and poles of which coincide in s-plane ($s_1^{\text{п}}=-0,333332$, $s_2^{\text{п}}=-0,2$) was obtained. Therefore, the conclusion may be made that the obtained DTF (5), (6) are equivalent to continuous object. Really, if CTF (4) is considered, it has two poles that corresponds completely to the obtained result. However, delay time differs: for Δt=1 s τ=5 s is obtained, and for Δt=2 s the value is τ=4 s.

Let us pass to the second stage – determine delay time. For this purpose DTF (5) is converted to CTF. As a result we obtain continuous transfer function

$$G(s)=\frac{1}{\left(\frac{1}{0,333332}s+1\right)\left(\frac{1}{0,2}s+1\right)}.$$

Let us recover continuous reaction of linear object at unit step input excitation [7]:

$$y(t)=1+1,500015e^{-0,333332t}-2,500015e^{-0,2t}.$$

To find delay time τ let us fix the first null measurement of transfer characteristic $y(t)$=0,018533 and time moment t=6 s. Let us equate relative to unknown value of transportation delay τ which takes the form:

$$0,018533=1+1,500015e^{-0,333332(6-\tau)}-$$
$$-2,500015e^{-0,2(6-\tau)}.$$

Supposing τ=6 s we decrease iteratively value $\tau=\tau-\varepsilon$ till we obtain numerical solution of equation with specified accuracy ε. At ε=0,01 s delay time τ=5,2 s. Comparing the obtained results with the initial function (4) it is seen that object CTF is completely recovered:

$$G(s)=\frac{1}{\left(\frac{1}{0,333332}s+1\right)\left(\frac{1}{0,2}s+1\right)}e^{-5,2s}.$$

The given object has two poles $s_1^{\text{п}}$=–0,333333 and $s_2^{\text{п}}$=–0,2. Let us take ε=0,05 s and determine $\Delta t_{\min}$, $\Delta t_{\max}$. Substituting $s_1^{\text{п}}$=–0,333333, $s_2^{\text{п}}$=–0,2 and ε=0,05 into formulas (2) and (3) we obtained respectively

$$\Delta t_{\min}=-\frac{\ln(1-0,05)}{|\max(-0,333332;-0,2)|}=\frac{\ln(0,95)}{-0,2}\approx 0,26\text{ s},$$

$$\Delta t_{\max}=-\frac{\ln(0,05)}{|\min(-0,333332;-0,2)|}=\frac{\ln(0,05)}{-0,333332}\approx 8,99\text{ s}.$$

Thus, to recover DTF by modified algorithm of V. Viskovatov the sampling increment Δt should be chosen in the range (0,26; 8,99).

To synthesized control system we can now chose a sampling increment multiple to delay time τ=5,2 s. In the range (0,26; 8,99) there are several of such (for example, 1,3 s; 2,6 s; 5,2 s). Let us take the sampling increment Δt=5,2 s and construct digital controller with Smith compensator.

Structural scheme of Smith compensator is given in Fig 1. Let the desired input action x be unit step function. Let us construct time optimal regulator $R(z)$.

Then: $G_0(s)=\dfrac{1}{(s+0,333332)(s+0,2)}$, $e^{-\tau s}=e^{-5,2s}$.

Object DTF for sampling increment Δt=5,2 s obtained by modified algorithm of V. Viskovatov takes the form:

$$G(z)=\frac{0,381405z^{-1}+0,150899z^{-2}}{1-0,530149z^{-1}+0,062453z^{-2}}z^{-1}.$$

Whence $G_0^{\text{м}}(z)=\dfrac{0,381405z^{-1}+0,150899z^{-2}}{1-0,530149z^{-1}+0,062453z^{-2}}$, d=1. Regulator DTF determined by the theory of polynomial equations [8] by DTF $G_0^{\text{м}}$, has the form:

$$R(z)=\frac{1,878625-0,995951z^{-1}+0,117327z^{-2}}{1-0,716517z^{-1}-0,283483z^{-2}}.$$

The results of modeling are given in the form of diagrams of transfer processes $y(t)$ (Fig. 2) and change of control action $u(t)$ (Fig. 3).

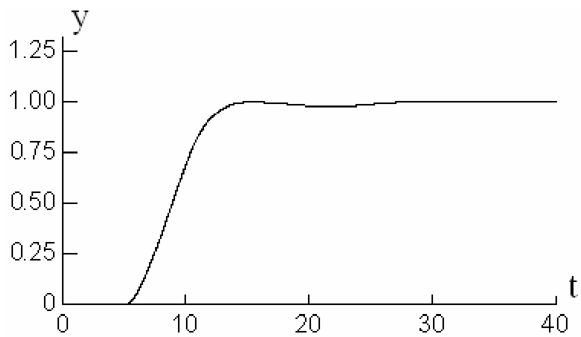

Fig. 2. *Transfer process at object output*

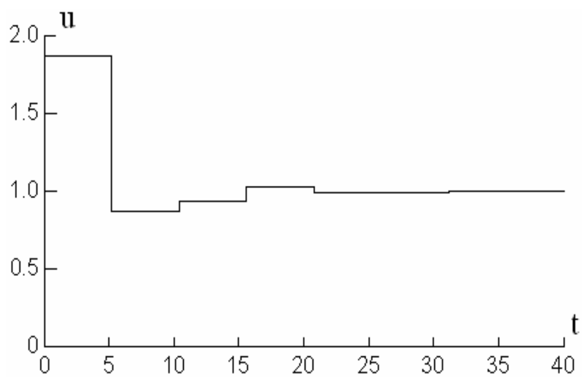

Fig. 3. *Control action*

The results of modeling showed that the obtained digital model of the object with delay allows adapting digital regulator with Smith compensator.

The algorithm for obtaining discrete model equivalent to continuous object by initial data of in-output variables is suggested in the given paper. The algorithm includes the following stages: 1) object identification by the criterion allowing us to recover DTF equivalent to the object; 2) delay time determination by the obtained object DTF; 3) determination of the range ($\Delta t_{\min}$, $\Delta t_{\max}$) for selecting sampling increment allowing identifying the equivalent to object DTF by modified algorithm of V. Viskovatov. The developed algorithm may be used at automation of technological processes possessing significant delay.

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AUTOMATED SYSTEM FOR STUDYING FEEDBACK REGULATORS

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Bundled software intended for realization of different control algorithms constructed on the basis of functional units on medium-priced industrial controllers have been considered. The example of programming in a language of functional block diagrams of algorithm of real processing automation is given.

Introduction

Recently to create automated control systems of technological processes (TP ACS) different technological programming languages available not only to programmer understanding but industrial engineers as well have been widely adopted. As a result, at present there are program packages for developing MMI and software of operator stations of TP ACS (SCADA) [1]. Owing to the fact that technological languages are easily unified a great many of such program packages is developed and moreover, proper programming languages are developed for them. To order somehow this process the standard of International Electrotechnical Commission IEC-1131-3 was accepted in 1993 [2]. The standard describes five programming languages of the programmed logic controller (PLC): *Sequential Function Chart* (*SFC*), *Function Block Diagram* (*FBD*), *Ladder Diagrams* (*LD*), *Structured Text* (*ST*), *Instruction List* (*IL*) [3]. Languages ST and IL are the most popular among programmers as they included the most common operators of programming languages of the type *Pascal* and *Assembler*.

Practice showed that the language of **functional blocdiagram (FBD)** is the clearest for industrial engineers. Language FBD serves for constructing and detailed description of control algorithms of technological processes. It allows a user to construct block diagram of control algorithm consisting of library blocks for a system of any complexity. Software complex «AKIAR» developed by programmers of the enterprise «NPO VEST» (Tomsk) in collaboration with information-measuring technology department at Tomsk State University of Control Systems and Radio electronics allows working with this very programming language and has a number of peculiarities discriminating it from similar software products. These peculiarities will be considered later and now let us pay attention to the fact that standard of IEC IEC-1131 is of voluntary character therefore we tried to conform but nevertheless developed our own library of functional blocks.

Software complex «AKIAR»

Software complex «AKIAR» includes all main possibilities of SCADA-systems. The analogue of such program is development system of programming algorithms «KONGRAF» («MZTA», Moscow) for regulators of «MS» type constructed at expensive microcontrollers. Software complex «AKIAR» is intended for working with regulators constructed at inexpensive microcontrollers. «AKIAR» combines graphics editor of functional blocks and program of modeling TP ACS which are intuitively clear for users having general idea of SCADA-systems. The significant advantage of program complex «AKIAR» over the system «KONGRAF» is the system of input, output and indication of industrial regulator parameters independent on control algorithm. Such system has flexible logic, allows denoting parameters in English and Russian, has tree-like (structured) menu.

Such powerful program packages of SCADA-systems as «*Genesis*», «*Trace Mode*», «*Genie*» are multifunctional and intended first of all for large-scale TP ACS. Such systems require powerful and expensive industrial controllers as well as significant temporary expenditures for modeling transfer processes for their realization. Use of expensive controllers in the field of heat and power engineering and especially housing and communal services for heating systems, hot-water sup-