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GRAPH MODELS AND ALGORITHM FOR STUDYING THE DYNAMICS OF A LINEAR STATIONARY SYSTEM WITH VARIABLE DELAY

Ubaydullaeva Sh.R. – c.t.s., associate professor, "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" National Research University

Abstract

In this paper, we consider the problem of studying the dynamics of linear objects with variable delay based on graph models. Due to the variable delay value, the output signal of the variable delay link will be deformed on the time axis. The function that is the output signal of the link will either be " compressed "on the time axis with respect to the input function, or «stretched". The conditions of physical realizability of the variable delay link are given. The physical properties of the variable delay link and the commonality of certain stages in the formation of models of systems with constant and variable delay are taken into account. On this basis, a graph of transition states is constructed and relations are obtained for calculating processes in a linear system with variable state delay. A linear system with variable delay can be studied using matrix equations. Graphs of transition states, allow you to bypass time-consuming calculations, to exclude operations associated with the lack of density of the matrices. The above scheme can also be used to calculate processes in systems with variable control delay

Keywords: dynamic object with delay, linear system with variable delay, graph model of the system, calculation of dynamic processes.

Introduction. The use of digital devices for control purposes, the need to process large amounts of information and transmit them over long distances using modern means of communication, computer networks, and the inclusion of a human operator in the control process have created prerequisites for the emergence of such control system structures that contain variable delay links [1-5]. Variable periodic delay can lead to the phenomenon of resonance, in which a closed system becomes unstable even if it is stable at any constant delay. On the other hand, the use of a lag model, even if not very accurate, usually allows you to significantly improve the dynamics of automatic control systems. Thus, the problem arises of estimating the variable delay in real time, perhaps even with not very high accuracy. Network time services and real-time clocks of computers are of little use here due to their low accuracy and reliability [6-10]. In real automatic control systems with a network component, such delays of various levels occur regularly. This is due to the peculiarities of the TCP/IP protocol when passing network packets through routers. These delays have not been sufficiently investigated. Their research is necessary to create algorithms for identifying the delay and adapting to the delay [11]. Many mathematical models of technological processes are dynamic objects with a delay [12]. The lag effect makes it difficult to stabilize and reduces the quality indicators of the systems [13]. In this paper, we consider continuous linear objects with variable delay in the feedback loop. But the process calculation algorithm can also be used for systems with variable control lag.

Materials and methods. Variable delay unit.

In the study of systems with variable delay, the concept of a variable delay link is introduced. This link differs from the constant delay link in a number of properties. The mathematical relationship between the input signal x (t) and the output signal y (t) of the constant delay link is known:

$$y(t) = \begin{Bmatrix} x(t-\tau), \tau \ge 0, & t \ge t_0 + \tau \\ 0, \quad\quad , & t \le t_0 + \tau \end{Bmatrix}$$

The output signal fully reproduces the input signal after the time $t_0 + \tau$.

Let the delay value be a function of the independent variable *t*:

$$\tau = \tau(t).$$

Due to the variable value of τ, the output signal of the variable delay link will be deformed on the time axis. The function y(t), which is the output signal of the link, will either be "compressed" on the time axis with respect to the input function x(t), or "stretched".

But no matter how the delay value τ(t) changes, the initial and final values of the function x(t) cannot change. Moreover, although the variable delay link deforms the input signal function x(t) on the time axis, the output signal function y(t) will reproduce all the instantaneous values of the function x(t) under both "compression" and "stretching".

We present the conditions for the physical realizability of the variable delay link. One of them is that the rate of growth of the delay should not exceed the rate of the natural passage of time, otherwise the input signal will never be reproduced at the output of the link. Since the speed of the natural course of time is equal to one (dt/dt=1), the variable delay function must satisfy the relation:

$$\frac{d\tau(t)}{dt} \le 1 \text{ для } t > 0.$$

The advance of the output signal in relation to the input signal is physically realizable, so the following condition for the physical realizability of the variable delay link:

$$\tau(t) \ge 0.$$

In addition to these conditions, restrictions are imposed on the negative values of the derivative *dτ/dt*: the duration of the negative values of *dτ/dt*. Mathematically, this is written as:

$$(t_2) + \int_{t_1}^{t_2} \frac{d\tau(t)}{dt} dt \ge 0.$$

We give a strict definition of the variable delay link.

Definition 1. A variable delay link is an element of the system whose properties are determined by the following conditions: 1. Given a certain function *τ(t)*, called the variable delay function, a set of input *X* and output *Y* functions with elements *x(t)* and *y(t)*;

2. Given a set of time points *T* with the values: t_0-the moment of the beginning of the observation of the output

function *y(t)*, t_b-the moment of the end of the observation of the output function *y(t)*, and segments:

- $\tau(t_0)$ is the delay of the initial value of the input function *x(t)*,
- $\tau(t_b)$ is the delay of the final value of the input function *x(t)* specified on the segment $[t_0 - \tau(t_0),\ t_0]$.

3. The variable delay function satisfies the following relations:

$\tau(t) \geq 0$, for everyone $t \in T$; $\frac{d\tau(t)}{dt} \leq t$ for $t > t_0$;

$\tau(t_2) + \int_{t_1}^{t_2} \frac{d\tau(t)}{dt}\, dt \geq 0$ for $t_1 \leq t \leq t_2$;

where $[t_1, t_2]$ the length of time on which $\frac{d\tau(t)}{dt} < 0$.

4. The input and output functions satisfy the equality

$$y(t) = x[t - \tau(t)]$$

and with $t = t_b$ we have $x(t_0) = y(t_b)$,

$$t_b - \tau(t_b) = t_0.$$

The delay function that meets all the requirements of definition1 can be either a linear or a nonlinear function of time. A number of practical problems allow us to represent the function $\tau(t)$ as a linearly time-varying function

$$\tau(t) = \tau + kt, \qquad (1)$$

where $\tau_0 \geq 0, k = const.$

For expression (1), the condition of the physical realizability of the variable delay link can be written as $k \leq 1$. For *k=0*, the function $\tau(t) = \tau_0 = const$. We get an expression for the constant delay link. For $k < 0$, the function τ (t) is a linear decreasing function. In this case, for the time values $t \leq \tau_0 / k$, the delay must be considered equal to zero, or some constant value τ_{min} for all time values $t \geq (\tau_0 - \tau_{min})/k$.

For k>0, the delay is a linearly increasing function. A system with a linearly increasing delay is always unstable due to the continuous growth of the delay. If there is a certain maximum value of the delay τ_{max}, then the stability of the system will depend on the value of this maximum.

In the case of a link with a nonlinear delay, the delay function depends not only on time t, but also on the input or output function, or both together,

$$\tau = \tau[t, \eta(t)], \qquad (2)$$

where the function $\eta(t)$ can take the values

$$\eta(t) = x(t), \eta(t) = y(t),$$

$$\eta(t) = \eta[x(t), y(t)].$$

Of course, the delay function in the form (2) satisfies all the conditions of definition1.

Linear system with variable delay in the feedback loop

Now we turn to the consideration of a linear system with a variable delay in the feedback loop (Fig.1).

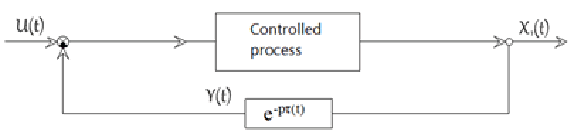

Figure .1. Linear system with variable delay in the feedback loop.

The differential equation of the system has the form:

$$\frac{dx_1(t)}{dt^n} + a_{n-1}\frac{dx_1(t)}{dt^{n-1}} + \ldots + a_0 x_1(t) + x_1(t - \tau(t))) = u(t) \qquad (3)$$

Here, the physical picture of the processes is somewhat different than in a system with a constant delay. Due to the variability of the delay value, the output signal $x_1(t)$, passing through the delay link, is deformed on the time axis (either "compression" or "stretching" of the signal occurs, although all instantaneous values are preserved). The duration of the output signal of the variable delay link *y(t)* is different from the duration of the "recorded" signal $x_1(t - \tau(t))$. This duration will be determined by the moment when the value $x_1(t_0)$ appears at the output of the variable delay link. By definition of a variable delay link

$$x_1(t_0) = y(t_1) \qquad (4)$$

$$t_1 - \tau(t_1) = t_0 \qquad (5)$$

By determining the moment when the instantaneous value of the signal $x_1(t_0)$ appears at the output of the delay link from equation (4), we can find the output process of the system in the time interval $[t_0, t_1]$. The differential equation (3) is replaced by the corresponding system of differential equations of the 1st order. This system of equations can be written in vector form:

$$\frac{d\bar{X}}{dt} = \bar{A}\bar{X}(t) + \bar{B}\, u(t) + \bar{C} x_1(t - \tau(t)) \qquad (6)$$

with the initial function $\varphi_0(t) = x_1(t)$ for $t_0 - \tau(t_0) \leq t \leq t_0$.

To solve equation (6), we use the Laplace transform:

$$p\bar{X}(p) = \bar{A}\bar{X}(p) + \bar{B}\, u(p) + \bar{C}\varphi_0(p) + \bar{X}(0^+), \qquad (7)$$

where $\varphi_0(p) = L\{\varphi_0(t)\}$, $\varphi_0(t)$ is the given initial function defined on the initial set $[t_0 - 0, t_0]$.

Performing elementary transformations, we find

$$X(p) = G(p)Bu(p) + G(p)C\varphi_0(p) + G(p)X(0^+) \qquad (8)$$

where $G(p) = (pI - A)^{-1}$.

Applying the inverse Laplace transform to expression (8), we get:

$$(t) = L^{-1}\{G(p)Bu(p)\} + L^{-1}\{G(p)C\varphi_0(p)\} + +L^{-1}\{G(p)\}X(0^+) \qquad (9)$$

Equation (7) describes the processes in the system on the segment $[t_0, t_1]$. Since) the function $\varphi_0(p)$ is known for $t_0 - \tau(t_0) \leq t \leq t_0$, then equation (7) turns into an ordinary algebraic equation and is solved by any of the known methods for these equations. To find the value of the end point t_1, use the relation $t_1 - \tau(t_1) = t_0$. Solving this functional equation with respect to t_1, we find the desired point.

Let us now take the point t_1 as the new starting point. This allows you to proceed to the next step of solving equation (6). For the time interval $[t_1, t_2]$, the previous solution will play the role of the initial function. Substituting $\varphi_1(p) = x_1(p)$ in equation(7), we get:

$$X(p) = G(p)Bu(p) + G(p)C\varphi_1(p) + G(p)X(t_1),$$

where from

$$X(t) = L^{-1}\{G(p)Bu(p)\} + L^{-1}\{G(p)C\varphi_1(p)\} + +G(t)X(t_1) \qquad (10)$$

Expression (10) is the solution of equation (6) on the interval $[t_1, t_2]$, where the end point t_2 is determined from the functional equation: $t_2 - \tau(t_2) = t_1$. In this way, you can define the processes for subsequent time intervals.

So, a linear system with variable delay can be studied using matrix equations and the Laplace transform. But the relation (7) can also be obtained with the help of transition state graphs, which make it possible to bypass time-consuming calculations and exclude operations related to the lack of density of the matrices [14].

The graph of the transition states (TSG) of the system with variable delay for time intervals *$t \in [t_k, t_{k+1}]$ (k=0,1, …, N)* is shown in Figure 2.

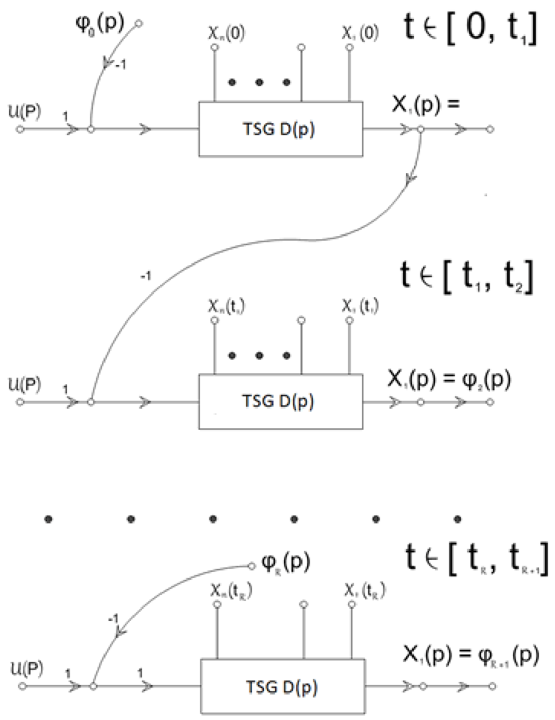

Figure 2. The graph of the transition states (TSG) of the system with variable delay.

We formulate the stages of calculating processes in a linear system with variable delay (this method can also be used to calculate processes in a system with variable delay in a direct chain):

1. A graph model of the system is built as a union of graph models of its elements.

2. The end point of the time interval $[t_k, t_{k+1}], k = 0,1, \dots, N$ is determined from the equation $t_{k+1} - \tau(t_{k+1}) = t_k$.

3. For the interval $[t_k, t_{k+1}], k = 0,1, \dots, N$, relations are determined for calculating the processes in the system:

$$X(p) = Q(p)X(t_k) + [R(p) \vee R_1(p)]u(t_k) + +c[\varphi_k(p) \vee (u(p) - \varphi_k(p))]S(p), \quad (11)$$

where $R_1(p)$ – null matrix, $c = 1 \ \vee -1$.

4. The initial function is determined $\varphi_{k+1}(p) = x_1(p)$.

5. The inverse Laplace transform is performed for the relation

$$X(t) = Q(t - t_k)X(t_k) + [R(t - t_k) \vee R_1(t - t_k)] u(t_k) + cD_k(t - t_k), \quad (12)$$

where

$$D_k(t - t_k) = L^{-1}\{\varphi_k(p)S(p)\} \vee L^{-1}\{[u(p) - \varphi_k(p)]S(p)\}.$$

6. The inverse Laplace transform is performed for the relation

$$X(t_{k+1}) = Q(t_{k+1} - t_k)X(t_k) + [R(t_{k+1} - t_k) \vee \vee R_1(t_{k+1} - t_k)u(t_k) + cD_k(t_{k+1} - t_k).$$

7. Go to point 3.

Determination of the output process in a system with a linear-decreasing delay in the feedback circuit.

We define the output process in the system, the block diagram of which is shown in Fig.4. The parameters of the links: *k=1, a=0, b=2,* the delay is a linear-decreasing function-$\tau(t) = 3 - 0.5t$, $\tau_{min} = 0.5$ The initial function given from the initial set E_0 $(t - \tau(t_0) \le t \le t_0)$) is equal to ϕ(t)=0, the initial conditions are zero.

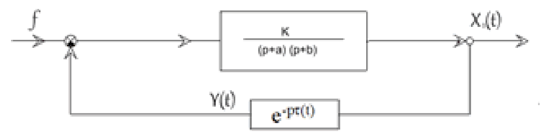

Figure.3. System with a linearly decreasing delay in the feedback loop.

The end of the first segment $[t_0, t_1]$ on which the process is defined is found from the equation $t_1 - (3 - 0.5t_1) = 0$, from which $t_1 = 2$. For the segment [0,2], the graph model of the system has the form shown in fig.4.

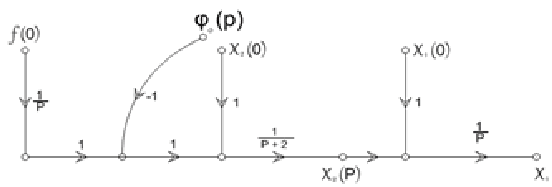

Figure 4. Graph model of the system for the segment [0,2]

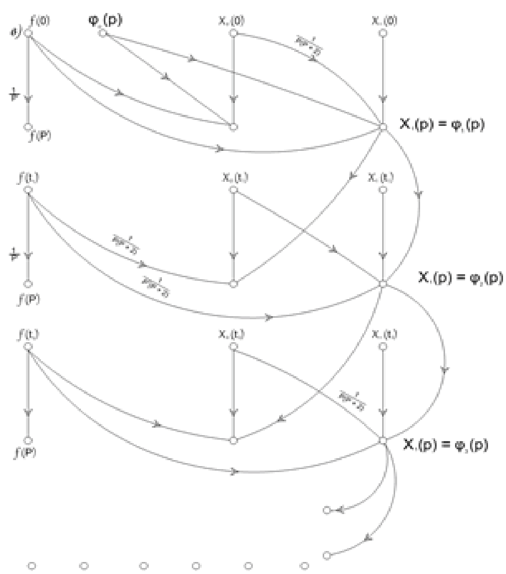

Figure 5. The topological model of the system

From the consideration of the graph, we can write:

$$x_1(p) = \frac{1}{p^2(p+2)}; \quad x_2(p) = \frac{1}{p(p+2)}.$$

Let's denote $\varphi_1(p) = x_1(p)$. Going to the originals, we will have

$$x_1(t) - 0.25^{-2t} - 0.25 + 0.5t; \; x_2(t) = 0.5(1 - e^{-2t})$$

From the last two relations, we find the values of the coordinates at the moment of time

$$t = 2; \; x_1(2) = 0.755, \; x_2(2) = 0.491.$$

The end of the second segment $[t_1, t_2]$is found from the equation: $t_2 - \tau(t_2) = t_1$where $t_2 = 3.3$.The solution obtained on the first segment, $x_1(t)$, is the initial function for the processes on the segment [2,3.3], which is clearly seen from the topological model of the system shown in Figure 4.

Let's define the Laplace transform of the system state variables (fig.3):

$$x_1(p) = \frac{f(t_1)}{p^2(p+2)} + \frac{x_2(t_1)}{p(p+2)} + \frac{x_1(t_1)}{p} =$$
$$= \frac{1}{p^2(p+2)} + \frac{0.491}{p(p+2)} + \frac{0.755}{p} - \frac{1}{p^3(p+2)}.$$
$$= \frac{1}{p(p+2)} + \frac{0.491}{p+2} - \frac{1}{p^2(p+2)^2}.$$
$$x_2(p) = \frac{f(t_1)}{p(p+2)} + \frac{x_2(t_1)}{p+2} - \frac{\varphi_1(p)}{p+2} =$$
$$= \frac{1}{p(p+2)} + \frac{0.491}{p+2} - \frac{1}{p^2(p+2)^2}.$$

Denote $\varphi_2(p) = x_1(p)$.

Moving on to the originals, we will have

$$x_1(t) = 0.0045e^{-2(t-2)} + 0.625(t-2) -$$
$$-0.125(t-2)^2 - 0.125(t-2) + e^{-2(t-2)} + 0.7505.$$
$$x_2(t) = -0.134e^{-2(t-2)} - 0.25(t-2) +$$
$$+0.25(t-2)e^{-2(t-2)} - 0.625.$$

The coordinate values at time $t_2 = 3.3$ are the initial conditions for the next time interval. From the last relations we have $x_1(3.3) = 1.309, \; x_2(3.3) = 0.352$.

Let us determine the moment of time t_3 from the equation $t_3 - \tau(t_3) = t_2$, we get $t_3 = 4.2$. Since the initial conditions and the initial function for the segment [3.3,4.2] are found, then from the consideration of the graph model (Fig. 4) we will have:

$$x_1(p) = \frac{0.245}{p^2(p+2)} + \frac{0.352}{p(p+2)} + \frac{1.309}{p} -$$
$$-\frac{\varphi_1(p)}{p^3(p+2)} - \frac{0.431}{p^2(p+2)^2} + \frac{1}{p^4(p+2)^3},$$
$$x_2(p) = \frac{0.245}{p^2(p+2)} + \frac{0.352}{p} - \frac{1}{p^2(p+2)^2} -$$
$$-\frac{0.491}{p(p+2)^2} + \frac{1}{p^3(p+2)^3}.$$

$\varphi_3(p) = x_1(p)$, where from

$$x_1(t) = 0{,}021(t-3{,}3)^2 - 0{,}219(t-3{,}3)^2 +$$
$$+0{,}312(t-3{,}3) - 0{,}3125 * (t-3{,}3)^2 e^{-2(t-3{,}3)} +$$
$$+0{,}123(t-3{,}3)e^{-2(t-3{,}3)} + 1{,}329 - 0{,}02e^{-2(t-3{,}3)};$$
$$x_2(t) = 0{,}0625(t-3{,}3)^2 - 0{,}4375(t-3{,}3)^2 +$$
$$+0{,}15625(t-3{,}3) * e^{-2(t-3{,}3)} +$$
$$+0{,}04e^{-2(t-3{,}3)} + 0{,}312.$$

The values of the coordinates at the point $t_3 = 4{,}2$ are found from the obtained relations:

$$x_1(t_3) = 1{,}370, x_2(t_3) = 0{,}05.$$

From the calculations performed, it is clear that the lengths of the segments on which the solution is found decrease with the growth of the step number. This is due to the fact that the delay value decreases. Let's determine what the delay will be at the point t_3. We will have $\tau(t_3) = 0{,}9$. Since $(t_3) > \tau_{min}$, it is necessary to continue to consistently find a solution to $x_1(t)$ with a decreasing step length.

In the next step $[t_3, t_4]$from the equation $t_4 - \tau(t_4) = t_3$ we get $t_4 = 4{,}8$ and determine the state variables from the relations:

$$x_1(p) = \frac{1{,}37}{p} + \frac{0{,}05}{p(p+2)} + \frac{1}{p^2(p+2)} -$$
$$-\frac{0{,}245}{p^2(p+2)^4} - \frac{0{,}352}{p^2(p+2)^2} - \frac{1{,}309}{p^2(p+2)} +$$
$$+\frac{1}{p^2(p+2)} \frac{0{,}491}{p^3(p+2)^3} - \frac{1}{p^5(p+2)^4};$$
$$x_2(p) = \frac{0{,}05}{p(p+2)} + \frac{1}{p^2(p+2)} - \frac{0{,}245}{p^3(p+2)^2} - \frac{0{,}352}{p(p+2)^2} -$$
$$-\frac{1{,}309}{p(p+2)} + \frac{1}{p^3(p+2)^3} \frac{0{,}491}{p^2(p+2)^3} - \frac{1}{p^4(p+2)^3}.$$

The delay at the point $t_4$will have the value $\tau(t_4) = 0{,}6 = \tau_{min}$.

For all subsequent steps, the delay will not change, so the further calculation process should be performed in the same way, but with a constant delay. This example illustrates the complexity of processes in systems with variable latency. As you can see, as the step number increases, the view of the initial function becomes more complex, which leads to more and more time-consuming calculations. But the proposed approach is quite convenient for machine implementation. In addition, unlike the classical method, being, like the latter, fundamentally accurate allows you to completely eliminate the direct integration of a differential equation with a delayed argument, which is an important advantage of it.

Conclusions. The paper deals with the study of dynamic processes in linear systems with a variable delay signal. The method of dynamic graph models is used, which allows you to bypass time-consuming calculations, to exclude operations associated with the lack of density of matrices. The next stage of research is the use of graph modeling to calculate multidimensional linear continuous processes with variable delays in control channels. It should be noted that the wide spread of discrete control systems with a delay, in the circuit of which there are control computers, makes it relevant to develop effective methods and models for describing, analyzing and synthesizing such systems [16]. These questions in relation to multidimensional systems, nonlinear systems with various types of pulse modulation, relay and logic - dynamic systems are still not fully solved [17-21].

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