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Digital adaptive control with pulse width modulation of signals

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ABSTRACT

The paper presented research results of a digital control system for a dynamic plant with pulse-width modulation (PWM) of control impacts. As the control PWM signal is taken the pulse duty cycle, is calculated on each current cycle of the sample from the measured values. A control algorithm is proposed based on a hybrid application of the linear-quadratic optimization procedure and the theory of observers of minimal complexity. To ensure execution that the conditions of Astatism are met, the dynamic model of the plant is supplemented with a discrete integrator. The proposed approach makes it possible to reduce hardware costs and increase the robustness of the control system due to the exclusion of operations for digital–analogue transformations of signals. The proposed algorithm for digital control of a dynamic plant with varying duty cycle values of the PWM signal shows that the PWM model turned out to be linear and practically inertia less, which makes it easy to take into account the modulator model, which significantly simplifies the solution of the problem of synthesizing a control system for a dynamic plant. The possibility of receiving a high-quality modulated control signal allows for significant suppression of signal pulsations and high control accuracy.

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1. INTRODUCTION

One of the urgent challenges of modern control theory is to ensure the required behavior of the control system for dynamic plants, the parameters of which change widely in the process of the functioning of the system [1]–[4]. The standard control laws are widely used in industry, although they are relatively simple for their implementation in control problems and are reliable, they are linear and keep their parameters constant throughout the entire functioning cycle of the plant. On the other hand, existing and using industrial units are nonlinear and non-stationary, which significantly complicates the solution of the problem of process control in real time.

Existing methods for researching the dynamics of a control system with a pulse-width modulation (PWM) modulator are based on recurrent methods or methods using phase plane concepts [5]–[7]. At present, there are a large number of systems for research of which well-known approaches are not suitable, or fundamental difficulties arise associated with non-standard operating modes of pulse-width modulators. In addition, in multidimensional control systems with PWM modulators, pulse repetition periods can be different, that is, the modulator operating modes are asynchronous [8]. In this case, the research methods used encounter some troubles associated with the calculation of output variables from the modulation characteristics of pulse elements, which becomes an additional source of difficulties when studying the operating modes of pulse parts of the control system [9]–[12].

In such situations, the most promising are the applications of adaptive methods based on the identification of the control plant [13]–[16]. The disadvantages of this approach are the complexity of implementing the identification procedure, requiring large computational costs and limited possibilities for changing the dynamic properties of the control system [17]–[19]. Another disadvantage of using typical linear regulation laws in industry is the presence of phase delay and high sensitivity to interference. To reduce these disadvantages various methods are used, such as including a phase-ahead filter in the regulator, correcting the properties of the regulator [20], [21].

In this case, in the generally accepted scheme for converting the control signal (from a digital representation into a pulse-width signal of a given power), it is assumed that a pulse-width (PWM) signal is generated, proportional to the calculated value by the input signal, and gain of the received signal. On the other hand, the required PWM signal is represented by a sequence of "ones" and "zeros" with a given operating cycle and a frequency not exceeding the controller frequency, which can be formed by software at the output of the microcontroller (MK). This leads to results in lower hardware costs and increased robustness of the entire control system. With this approach, the MK does not calculate the control signal itself; it calculates the duty cycle of the appropriate PWM signal under the input signal.

2. METHOD

Let the dynamics of a linear stationary discrete control system be described by a system of differential equations:

$$\mathrm{x(i+1) = Ax(i) + Bu(i);\ y(i) = Cx(i)} \tag{1}$$

where, $\mathrm{x \in R^n, u \in R^m, y \in R^r, (r < n)}$ – vectors of the state, controlled and measured outputs, respectively. A, B, C - matrices of the appropriate sizes of the observed and controlled influences. It is required to find an algorithm for calculating the duty cycle $q(i)$ of the control PWM signal in this a way that the closed-loop control system is sustainable, allowing the control system to be given the properties of Astatism and ensuring the necessary quality of transient processes during step changes in external influences. It is known that the duty cycle of a pulse-width modulated signal depends on the pulse duration (τ_u) and the pulse repetition period according to: $q(i) = \tau_u/T$. Taking this into account, the discrete model of the PWM signal can be represented by a difference equation of the following form:

$$u(i+1) = q(i), \tag{2}$$

where, $u(i)$ - discrete control signal.

In this case, if take into account that a rectangular signal is supplied to the input of the PWM unit, and the average value of the control signal for the period under consideration is determined at the output, then the PWM model can be represented as a linear-difference control of the first order, *i.e.* $Tu(i+1) + u(i) = q(i)$, where, T - time constant, characterizing the inertia of the process. Consider solving the problem of researching the dynamics of a control system with a pulse-width modulator. The control systems with pulse width modulation belong to the class of nonlinear systems. In this case, the pulse-width modulator in Figure 1 is one of the main elements of modern microcontrollers intended to control technological plants. The calculation of the control signal for the PWM circuit is carried out according to the following recurrence relation [22]:

$$y_{\sum i+1} = x_{i+1} - y_{i+1}, \tag{3}$$

$$y_{int\ i+1} = y_{int_i} + y_{\sum i} dt/T_0, \tag{4}$$

$$\begin{aligned} &if\ y_{int\ i+1} > a, then\ y_{i+1} = A, if\ y_{int\ j+1} < -a, then\ y_{i+1} = -A,\\ &if\ y_{int\ i+1} < a \wedge y_{int\ i+1} > 0 \wedge\ if\ y_{int} \le 0, \quad then\ y_{i+1} = 0, else\ y_{i+1} = y_i\\ &if\ y_{int\ j+1} > -a \wedge y_{int\ i+1} < 0 \wedge\ if\ y_{int} \ge 0,\ then\ y_{i+1} = 0, else\ y_{i+1} = y_i \end{aligned} \tag{5}$$

where x_{i+1} is the input signal of the modulator, y_{i+1} is the output signal of the modulator. A is the output signal of level, limited by relay element, $\alpha = A - t_i$, are the relay element of the dead zone, t_i is the pulse duration, $y_{int\ j+1}$ is the output signal of the modulator integrating element. T_0 is the time constant of the modulator integrating element, $y_{sum\ j+1}$ is the output signal of the summation element. The principle of operation of the modulator is to transform the input signal, *i.e.* error signal into a sequence of rectangular pulses. In this case, the duration of the rectangular signal is directly proportional to the magnitude of the error signal, as shown in Figure 2. Here Figure 2(a) a sawtooth signal and Figure 2(b) an output signal with PWM.

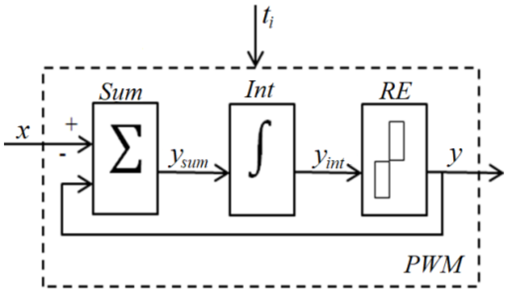
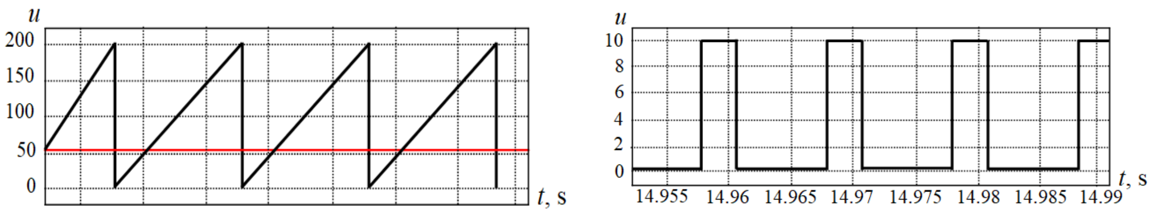


Figure 1. The structural scheme of the modulator: sum (summation operation); int (integration operation); and RE (limiting the control signal of a relay element with a hysteresis characteristic)



(a) (b)

Figure 2. Signal conversion using PWM: (a) sawtooth signals and (b) modulation output signals

In a control system, the error signal is determined by the difference between the given value and the current value of the controlled process. The output signal of the control plant is usually measured by a sensor, and in the absence of a sensor, the values of the output signal are determined from the mathematical model of the control plant. In this case, using the convolution theorem, the value of the output signal of the control plant at each time step is calculated by $y(t) = \int_0^t \omega(\tau_u)u(t-\tau_u)d\tau_u$, where $\omega(\tau_u)$ - weight function, determined by the transfer function of the plant; $u(t-\tau_u)$ - the input signal of the plant.

The algorithm generates a sawtooth signal, which is compared with the error signal. If the error signal e_s decreases, then the integrator slows down the growth of the error signal and overshoots the transient response of the control system. The error signal compensation depends on the time constant T_s. of the plant. The T_s. value is accepted to be equal to the pulse duration at each cycle. To limit the output system of the controller, a limitation on the differentiating component in the form $[U_{MAX}, -U_{MAX}]$ is used.

The modulator operation algorithm is as follows: A sawtooth signal is supplied to the modulator, which is compared with the control error signal. If the control signal is greater than the signal formed in the algorithm, then the output is logical 1, corresponding to the supply voltage, otherwise 0. It should be noted that the proposed algorithm for calculating the value of the PWM modulator control signal, implemented in microcontrollers, applies to both one-dimensional and multidimensional control systems. Let a multidimensional control system consist of two parts, including pulse-width (PWM) modulators and a linear continuous part of the system. The duration of the current pulse values at the output of each modulator is determined as $\tau_n^i = \begin{cases} \varphi^i[e(nT_i)]\ at\ \varphi^i[e(nT_i)] \le T_i; \\ T\ at\ \varphi^i[e(nT_i)] > T_i, \end{cases}$, where T_i is step discretization of a continuous signal at the modulator output; φ^i is modulation characteristics.

To synthesize the control algorithm, use a discrete model of a dynamic plant, described by a system of difference equations:

$$x(i+1) = Ax(i) + Bu(i)$$
$$y(i) = Cx(i) + Du(i) \quad (6)$$

where, A, B are numeric matrices; C, D are matrices consisting of zeros and ones; x is vector of the state; and y is vector of measured outputs.

To impart the property of Astaticity to the plant model of the control system, an additional discrete integrator is introduced into the control loop:

$$\mu(i+1) = \mu(i) + hy(i), \quad (7)$$

where, μ- the output of the integrator; h – the step of the discretization.

Then the discrete model of the equivalent plant has the following form:

$$\bar{x}(i+1) = \bar{A}\bar{x}(i) + \bar{B}\bar{q}(i)$$
$$\bar{y}(i) = \bar{C}\bar{x}(i) \quad (8)$$

where, $\bar{y}$- extended vector of measured output data, and matrices $\bar{A}, \bar{B}, \bar{C}$ are defined by (9):

$$\bar{A} = \begin{bmatrix} 1 \vdots 0 \vdots 0 \\ \dots\vdots\dots\vdots\dots \\ 0 \vdots 0 \vdots 0 \\ \dots\vdots\dots\vdots\dots \\ 0 \vdots \mathrm{B} \vdots \mathrm{A} \end{bmatrix},\ \bar{B} = \begin{bmatrix} 0 \\ \dots \\ 1 \\ \dots \\ 0 \end{bmatrix},\ \bar{C} = \begin{bmatrix} 1 \vdots 0 \vdots 0 \\ \dots\vdots\dots\vdots\dots \\ 0 \vdots \mathrm{D} \vdots \mathrm{C} \end{bmatrix} = [\mathrm{I} \vdots 0] \quad (9)$$

where, I is identity matrix. Should be taken into account, that depending on the number of controlled variables, the sizes of the matrices $\bar{A}, \bar{B}, \bar{C}$ have different values.

When solving the problem of synthesizing a control algorithm, we use a discrete controller based on a combination of a state controller and a Luenberger observer of minimal complexity [23]–[25]:

$$u(i) = F\hat{x}(i) = F\big(V\xi(i) + Uy(i)\big),$$
$$\xi(i+1) = \theta\xi(i) + Ky(i) + TBu(i), \quad (10)$$

where $\xi \epsilon R^{n-r}$ is a vector of the observer state, $\hat{x} \epsilon R^n$ is a vector of estimates of plant state variables, used in state controller. It is assumed that the matrices (θ, K, T, V, U) satisfy the conditions.

$$TA - \theta T = KC, UC + VT = I_n, \quad (11)$$

In this case, the poles of the closed-loop control system will consist of the poles of the state controller with the definition of eigenvalues and the observer. The vector of measured outputs C has a canonical structure $C = [I_r \ \vdots \ 0]$. The observer matrices are determined by the following relations:

$$T = [LI_{n-r}], U = \begin{bmatrix} I_r \\ -L \end{bmatrix}, V = \begin{bmatrix} 0 \\ I_{n-r} \end{bmatrix},$$
$$K = TAU = -(A_{22} + LA_{12})L + A_{21} + LA_{11},$$
$$\theta = TAV = A_{22} + LA_{12} \quad (12)$$

where, L is some $(n-r) \times r$ – matrix, defined by the controller; $A_{ij}(i, j = \overline{1{,}2})$ are blocks of matrix A obtained by splitting vector x into two components $x_{(1)} = y\epsilon R^r$ and $x_{(2)} = y\epsilon R^{n-r}$. Here $x_{(1)} = y\epsilon R^r$ and $x_{(2)} = y\epsilon R^{n-r}$ coordinates of the measured variable, $x_{(1)} = y\epsilon R^r$ and $x_{(2)} = y\epsilon R^{n-r}$ unmeasured coordinate variables. Based on the matrices A_{12} and A_{22} are formed, respectively.

Matrices F and L are determined using the linear-quadratic discrete optimization procedure:

$$F = -(I_m + B^T PB)^{-1} B^T PA, P = P^T > 0,$$
$$P = A^T PA + Q - A^T PB(I_m + B^T PB)^{-1}, E = E^T > 0, \quad (13)$$

$$L = -A_{22}EA_{12}^T(I_r + A_{22}EA_{12}^T)^{-1}, E = E^T > 0,$$
$$E = A_{22}EA_{12}^T + \psi - A_{22}EA_{12}^T(I_r + A_{12}EA_{12}^T)^{-1}A_{12}EA_{12}^T \quad (14)$$

Ensuring the stability of the closed-loop system, and the required quality of regulation is achieved by choosing the weighting coefficients of the matrix Q, $Q = Q^T \geq 0, \psi = \psi^T \geq 0$.

Let us represent the controller equation in the form:

$$\xi(i+1) = W\xi(i) + Sy(i);\ u(i) = M\xi(i) + Ny(i) \tag{15}$$

Then the matrices $W, S, M,$ and N are defined by (16).

$$W = \theta + TBFV;\ S = K + TBFU;\ M = FV, N = FU. \tag{16}$$

Thus, to solve the problem of synthesizing a discrete controller, it is necessary to find matrices F and L using (13), and (14), and the remaining matrices using (12), and (16).

By applying the proposed method to the plant, you can obtain a solution to the synthesis problem in the form of difference equations:

$$\bar{\xi}(i+1) = \bar{W}\bar{\xi}(i) + \bar{S}\bar{y}(i); q(i) = \bar{M}\bar{\xi}(i) + \bar{N}\bar{y}(i) \tag{17}$$

where $\bar{\xi}$ is a vector of the controller state. The dimension of which is determined by the difference between the dimension of the controlled plant and the number of its measured outputs. $\bar{W}, \bar{S}, \bar{M}, \bar{N}$ are extended parameter matrices of the plant.

To find the complete controller equation, we add a discrete integrator to (17). In this case, the equations of the desired astatic regulator will have the form:

$$\xi(i+1) = \begin{bmatrix} 1 & 0_{1\times2} \\ \bar{S}_{(1)} & \bar{W} \end{bmatrix} \xi(i) + \begin{bmatrix} 0 & h & 0 \\ \bar{S}_{(2)} & \bar{S}_{(3)} & \bar{S}_{(4)} \end{bmatrix} y(i), \tag{18}$$

where $\bar{S}_{(j)}$ and $\bar{N}_{(j)}$ $(j = \overline{1,4})$ - columns and elements of the corresponding matrices. The equation (18) represents a control algorithm that allows you to calculate the PWM control signal at the current discretization step of the measured quantities. Applying the z-transform to (18) and eliminating the $\bar{\xi}$ vector, we obtain the following relation:

$$q(z) = W_{uq}(z)u(z) + W_{lq}(z)l(z) + W_{wq}(z)\big(w_{zad}(z) - w(z)\big), \tag{19}$$

where, $W_{uq}(z), W_{lq}(z), W_{wq}(z)$ are the transfer functions of the controller. The control algorithm allows us to minimize the number of operations.

The control algorithm allows us to minimize the number of operations. The proposed method for synthesizing an algorithm for a control system with pulse-width modulation by eliminating the operation of converting an analogue signal into digital form makes it possible to increase the accuracy and reliability of the control system. The use of pulse signals as control impacts makes it possible to imagine the pulse-width modulator as a linear inertia less unit, which simplifies the solution of the problem of synthesizing a control algorithm and gives it possible to provide the values of pulsation that arises as a result of quantization of a continuous signal.

3. RESULTS AND DISCUSSION

The structure scheme of a dynamic plant control system with a PWM modulator is reduced as shown in Figure 3. The structure scheme of the control system, where q - the frequency of the PWM signal to generate the current control signal; u is control signal, l is moving the drive; g is angular displacement of the valve; ω is angular velocity of the rotor; and f is load. It is required to synthesize control systems for a dynamic plant with a discretization step $h = 0.00625$ *sec*. Applying the proposed control algorithm, we determine the transfer functions of the controller, $W_{uq} = \frac{-0.53(z-2.8)}{(z-0.02)}$, $W_{lq} = \frac{-0.45(z-0.93)(z-0.68)}{(z-0.97)(z-0.02)}$, $W_{uq} = \frac{30(z-0.986)(z-0.98)}{(z-1)(z-0.97)}$. Taking into account the negative shift of the arguments of discrete functions, the equation algorithm takes the following form:

$$q(i) = 1.99q(i-1) - 1.009q(i-2) + 0.19q(i-3) - 0.53u(i) + 2.53u(i-1) - \\ 3.44u(i-2) + 1.44u(i-3) - 4.5l(i) + 11.75l(i-1) - 10.1l(i-2) + 2.85l(i-3) + \\ 30e(i) - 59.6e(i-1) + 30.18e(i-2) - 0.58e(i-3).$$

As shown in Figure 4, the results of the simulation are presented by transient processes for the variables of the stabilization loop, obtained for a single-stage load applied at a certain point in time t. In this case, the equation (19) was used to model the control algorithm, the equation (5) was used for PWM, and a zero-order fixator with level quantization was used for the analog-to-digital converter (ADC). The graphs it can be seen that the quality of stabilization is quite satisfactory. In particular, in terms of regulating time, the dynamic error does not exceed 5%, and the error in the steady state is zero.

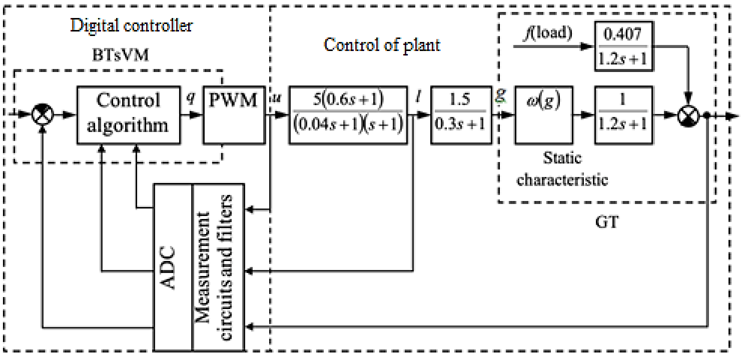


Figure 3. The structure scheme of the control system

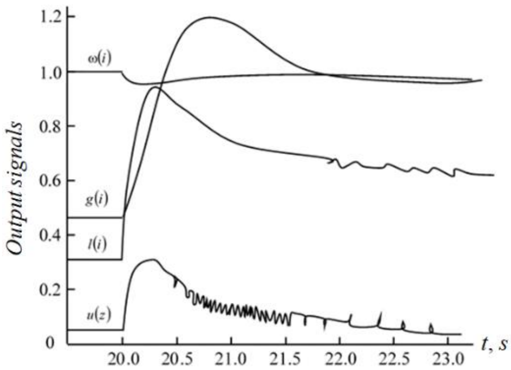


Figure 4. Results of analysis of transient processes of stabilization loop variables: $\omega(i)$ is angular velocity of the rotor; $g(i)$ is angular displacement of the valve; $l(i)$ is moving the drive; and $u(i)$ is control signal

4. CONCLUSION

The proposed algorithm for digital control of the pulse width of a PWM signal shows that the PWM model turned out to be linear and practically inertia less, which makes it easy to take this model into account when synthesizing the control algorithm. The pulse width calculated at the current discretization step from the measured variables is taken as the control PWM signal. The proposed the control algorithm based on a hybrid application of the linear-quadratic optimization procedure and the theory of observers of minimum complexity. To ensure that the conditions of Astaticity are met, the dynamic model of the plant is supplemented with a discrete integrator. The proposed approach allows it possible to reduce hardware costs and increases the reliability of the control system by eliminating digital-to-analogue conversion operations and forming a pulse-width modulated signal with slowness proportional to the calculated control signal. In the proposed digital control algorithm, the formed control signal obtained based on calculating the duty cycle of a pulse-width modulated signal shows that the PWM model becomes a linear and inertia less unit. This allows you to obtain a high-quality modulated control signal, providing significant suppression of signal pulsation and high control accuracy.

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BIOGRAPHIES OF AUTHORS

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