Adaptive pseudolinear compensators of dynamic characteristics of automatic control systems

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Abstract: Adaptive pseudolinear gain and phase compensators of dynamic characteristics of automatic control systems are suggested. The automatic control system performance with adaptive compensators has been explored. The efficiency of pseudolinear adaptive compensators in the automatic control systems with time-varying parameters has been demonstrated.

1. Introduction

In the systems of automatic control over objects, which characteristics change in the course of time, it is necessary to provide a purposeful change of dynamic characteristics of a controlling device. In most cases, it is realized by parametrization of proportional-integral differential controllers (PID controllers). These approaches are described, for instance, in [1, 2], however their realization concerns either identification or the use of special methods based on calculations according to the curve of the transient process. Both these approaches require a significant amount of time for controller tuning.

The current paper presents the research findings of automatic control system characteristics with PID-controller and cascade adaptive gain and phase pseudolinear compensators of dynamic characteristics. This adaptation method is characterized by the fact that in the process of control system operation the controller parameters do not change and correspond to the tuning, preceding the system start. Thus, only gain or phase shift on a proper compensator changes during automatic control system tuning. This tuning is applied when a process variable has variations connected with the change of the control object properties or disturbances. It allows ensuring a system stability and improving a transient process quality.

Compensators are classified into three groups: linear, nonlinear and pseudolinear. The main disadvantage of the linear compensator is that its parametrization influences both gain and phase-frequency characteristics of the system. In this case, during improvement of the phase-frequency characteristics of the system the gain-frequency characteristics will increase in mid and high frequencies that decreases the system stability. Moreover, when enhancing gain-frequency characteristics of the system, the phase-frequency characteristics of the open-loop system obtain a negative value close to $-\pi$, which significantly decreases system stability.

Investigations [6] show that the linear compensator adaptation procedure is possible only for a limited in range and nature parametrization of the control object even at using modern mathematical tools such as fuzzy logic. The nonlinear compensator usage is problematic due to phase-frequency characteristics dependence on the harmonic oscillations amplitude.

An adaptive pseudolinear compensator allows reaching the required gain- and phase- frequency characteristics. This compensator has two channels (gain and phase) that can be tuned independently. In addition, phase-frequency characteristics of adaptive pseudolinear compensators do not depend on harmonic oscillations amplitude.

Phase-, gain- and phase-gain compensators have become widely spread in comparison with other pseudolinear compensators [5]. The conducted investigations show that gain compensators are the most effective ones for adaptive systems realization. These compensators have no influence on system characteristics in a static mode. However, if variations of the process variable (PV) are present, they reduce the gain without any noticeable change of the phase shift. The application of these compensators provides a required quality of automatic control systems in the wide range of parametrization of the control object and the nature of disturbance influences. This compensator can be considered as a supplementary resource participating in the control action formation and enhancing the control quality.

2. Related work
The structure of the adaptive gain compensator proposed in [7] is shown in Figure 1. This compensator is connected in series with the controller.
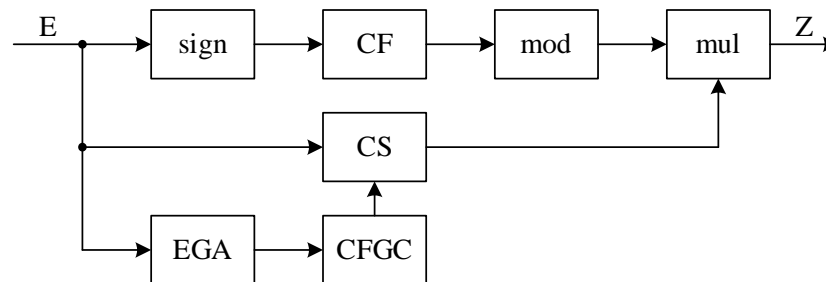

Figure 1. Block diagram of the adaptive gain compensator

Figure 1 has the following symbols: E – compensator input signal; sign – block of sign determination; CF – compensating filter; mod –modulus separator; mul – multiplication block; Z – compensator output signal; CS – compensator static gain; EGA – error gain analysis block; CFGC – correction block of compensating filter coefficient.

This compensator has been made on the base of the pseudolinear filter, which was imparted an additional property of parametric adaptation in addition to gain weakening (of frequency adaptation), consisting in high frequency attenuation.

The parametric adaptation is realized by means of changing the static gain of the compensating filter representing a linear dynamic element. In most cases this is an aperiodic element of the first order. If one uses the element with transfer function

$$W(s) = \frac{K}{Ts+1},$$
(1)

as a compensating filter, where K – static gain of the element, T –time constant of the element, the gain-phase frequency characteristic of the compensator at K=1, obtained as a result of harmonic linearization, will have the following view:

$$W(j\omega) = a + jb,$$
(2)

where $a = \dfrac{8}{\pi^2 \cdot \sqrt{1+T^2\omega^2}} \cdot \left(1 + \dfrac{1}{3} \cdot \cos(2\theta)\right)$; $b = \dfrac{8}{\pi^2 \cdot \sqrt{1+T^2\omega^2}} \cdot \left(\dfrac{1}{3} \cdot \sin(2\theta)\right)$; $\theta = -\text{arctg}\,\omega T$; ω - angular frequency of harmonic oscillations.

Analyzing the analytically presented gain-phase frequency characteristic of (2) it is possible to show that, in case of alternating the frequency, the gain-frequency characteristic of the compensator changes from K to zero. And the change of the phase frequency characteristic at different parameters

of the compensating filter occurs no more than by –20°. Moreover, the maximum phase shift of the aperiodic element of the first order (1) can reach –90°. The compensator operates in the following way. At the onset of variation of the output variable of the control object in the automatic control system (ACS) the gain of the compensator reduces automatically. This happens as a result of multiplication of the upper and middle branch signals.

Let us consider the case when K=1. In this case, the gain of the harmonic signal of the upper branch of the compensator will be less than 1. Therefore, the compensator gain overall will be less than 1 as well. In this connection the gain will be reduced with the increase in frequency. In cases when the gain change does not remove oscillations, the middle branch gain of the compensator changes automatically. The correction block of the compensating filter coefficient realizes this process according to the error amplitude value, determined in the block of the error amplitude analysis of ACS. The adaptation mechanism can be different: for example, linear or quadratic. Also, the gain change can be realized on the basis of the fuzzy logic apparatus [6].
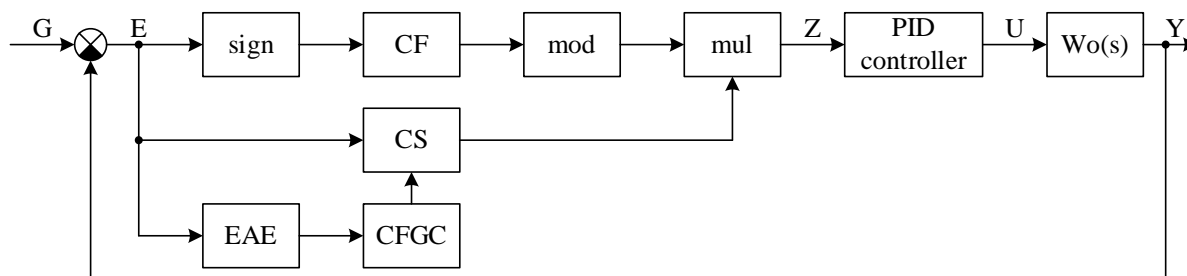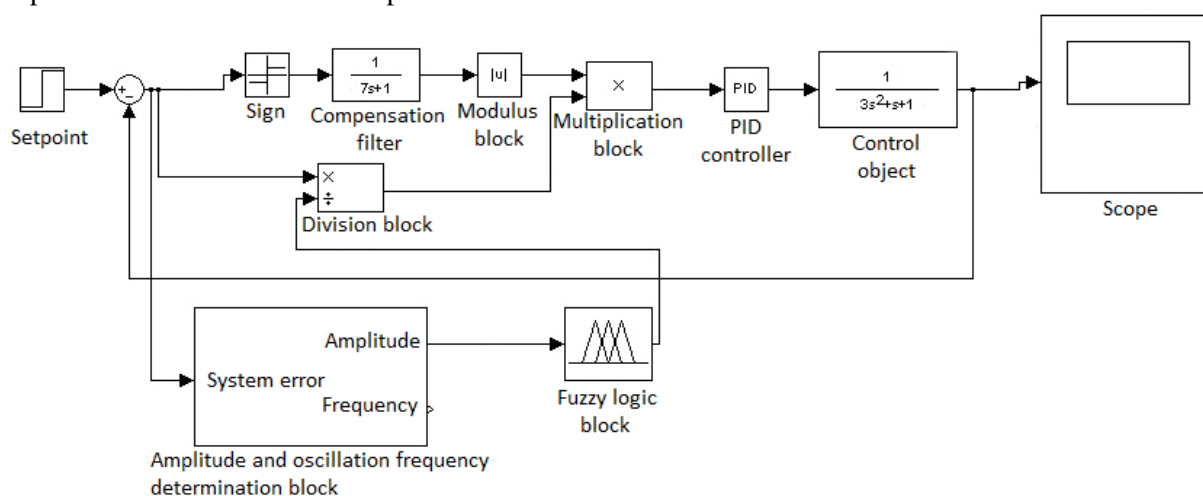
Figure 2 shows a block diagram of the automatic control system with the adaptive gain pseudolinear compensator.

Figure 2. Block diagram of the automatic control system with the adaptive gain pseudolinear compensator

Figure 2 has the following symbols: G – control system setpoint, U – control action, Y – control object output, Wo(s) – transfer function of the control object.

The investigation of the properties of the system with the adaptive compensator was conducted in the MATLAB 6.5 software package. Figure 3 shows acontrol system model with an adaptive gain compensator model performed in MATLAB. The compensator static gain was changed by means of the fuzzy logic apparatus. Defuzzyfication was conducted with the use of the center mass method. The procedures of determination of the error variation amplitude and realization of fuzzy logic have been represented in the form of the separate blocks.

Figure 3. Control system model with the adaptive gain pseudolinear compensator

Figure 4 shows transient processes for automatic systems with the 1st, 2nd and 3rd order objects. These automatic systems consist merely of a PID controller and a PID controller with the pseudolinear gain compensator. These curves represent the adaptation ability of the control system to change the control object parameters.
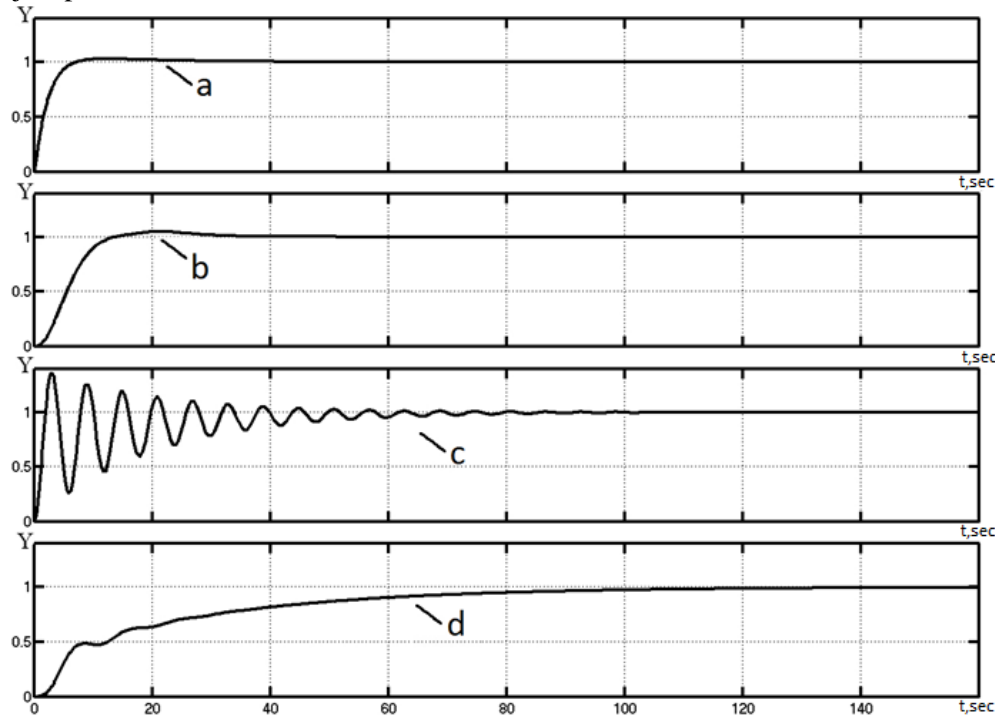

Figure 4. Curvatures of the transient processes for a single step excitation of ACS with the gain compensator

The control object was modelled by the second order element with transfer function

$$Wo(s) = \frac{Ko}{T_1^2 s^2 + T_2 s + 1},$$

where K_O – static gain of the control object, T_1 and T_2 – time constants of the control object.

Figure 4, a shows the nature of the transient process for a single step excitation of ACS with a PID controller without the compensator at the initial tuning of the controller, implemented according to Ziegler-Nichols method.

Figure 4, b shows a transient process for automatic system control with a PID controller and a compensator at the initial tuning of the compensator and controller.

Figures 4, c and d show transient processes after changing static gain of the control object from 10 to 1 and time constant T_2 from 20 to 1 sec. Value T_1^2 was considered to be equal to 3 sec. In addition, the gain and time constant of integration and differentiation of a PID controller, equal to K_p=2.4249, T_i=5.89, T_d=0.5419 correspondingly, did not change. The type of curve 4 shows that the quality of the automatic control system (ACS) with a compensator (figure 4, d) is much better than that of ACS without a compensator (figure 4, c) at the adjusted parameters of the control object.

Let us consider the adaptive phase compensator with transfer coefficient

$$W(s) = \frac{T_1}{T} \cdot \frac{Ts+1}{T_1 s + 1},$$

where T_1 and T – time constants of the integral-derivative element.

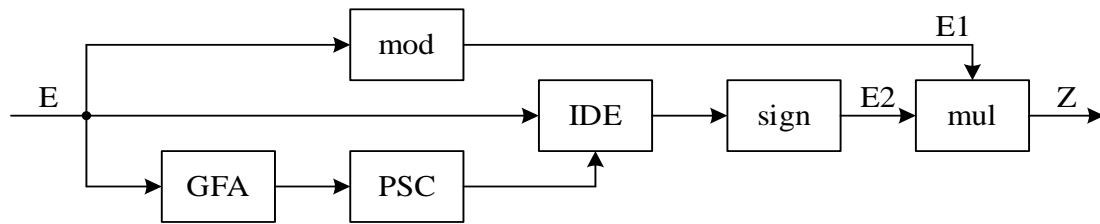Figure 5 shows the block scheme of the adaptive pseudolinear phase compensator.

Figure 5. Block scheme of the adaptive phase compensator.

Figure 5 contains the following symbols: GFA – gain and frequency analysis block, PSC – phase shift correction block, IDE – integral-derivative element.

Harmonic linearization coefficients of this compensator have the following view:

$$a = \frac{1}{\pi}(\pi - 2\alpha + \sin 2\alpha) \; ; \; b = \frac{1}{\pi}(1 - \cos 2\alpha) \,, \tag{3}$$

where $\alpha = \mathrm{arctg}\,\dfrac{\omega T(1-v)}{1+\omega^2 T^2 v}$; $v = \dfrac{T_1}{T}$.

The analysis of the compensator frequency characteristics shows that, when changing frequency and time constants (T_1 from 1 to 0,01 sec and T from 1 to 10 sec.), the phase characteristic undergoes transformations in the range from 0 to 78° and the decibel-log frequency response changes from 0 to – 4 dB. Such transformation of the decibel-log frequency response does not influence the stability margins of ACS.

This compensator realizes a phase shift, which magnitude depends on the values of time constants T and T_1. The input signal branches out and goes through three channels. The upper channel provides error modulus extraction. The middle channel consists of an integral-derivative element, a sign determination block and a multiplication block. The lower channel provides determination of the amplitude and frequency of oscillations at the compensator input and changing of the phase shift of the integral-derivative element by correcting time constant T. The output signal (Z) equals the multiplication of the output signals from the upper (E1) and middle (E2) channels.

When the variable variations as well as an error arise in ACS, the compensator increases time constant T automatically, which results in increase of v (3) and this, in its turn, increases phase-frequency characteristics (PFC). This property justifies the PFC analysis of the compensator having the following view:

$$\phi(\omega) = \mathrm{arctg}\,\frac{\dfrac{1}{\pi}(1 - \cos 2\alpha)}{\dfrac{1}{\pi}(\pi - 2\alpha + \sin 2\alpha)} \,.$$

In other words, the variation is suppressed by the rise of phase-frequency characteristic of ACS.

The determination of the time constant providing the required correction of the phase shift occurs in PCS block according to a decision rule, presented in the form of a piecewise linear function and obtained on the basis of the PFC set of an integro-differentiating element, corresponding to different values of time constants T. This function is made up on IDE phase-frequency characteristics series that varies with time constant T. The procedure of decision rule formation is based on the piecewise linear function construction that connects time constant T, providing maximal rise of phase-frequency characteristics, and the frequency of harmony oscillations that enter the compensator input [6].

The adaptive pseudolinear phase compensator, as well as the gain one, is connected in series to the control channel. The investigations of the phase corrector properties have been made by the example of ASC of the objects of the first and second order.

Figure 6 represents the curves of the transient process for a single step excitation in the control systems with a PID controller and a pseudolinear phase compensator. Curve 1 describes the transient process in ACS with a PID controller without the compensator and curve 2 describes the transient process in ASC with a PID controller and with the phase compensator. The automatic control system was studied with the same control object as in the case with the gain compensator considered above.

The parameters of the transfer function of the control object conforms to parameters that define the curve of the transient process in Figure 4, c. At that, the PID controller parameters did not change. Thus, the curves of the transient processes, represented in figure 6, characterize the possibility of the adaptive control by means of the pseudolinear phase compensator.
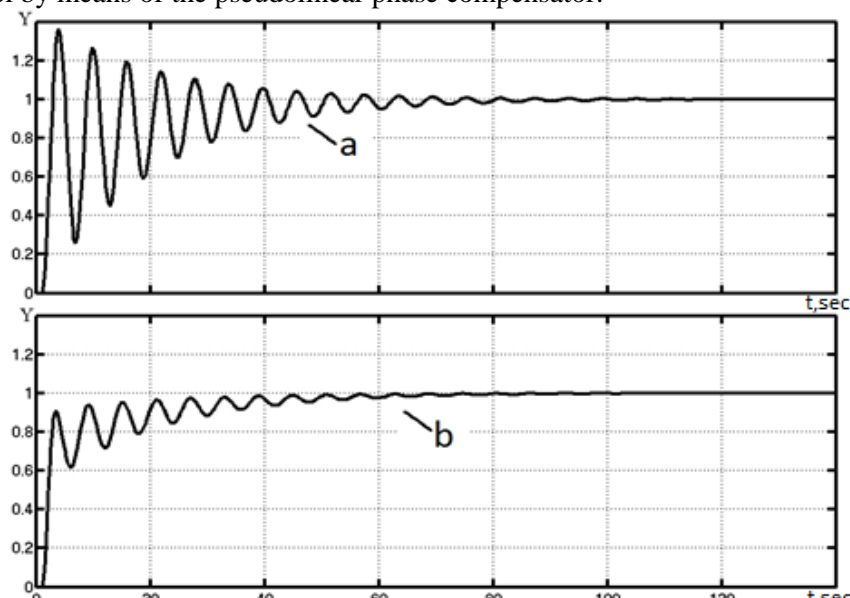

Figure 6. Curves of the transient processes for a single step excitation in the automatic control system with the phase compensator

3. Conclusion

When one applies the above-mentioned compensators practically, the question arises as to when it is better to use the gain compensator and when – the phase one. The investigation results have shown that the phase compensator is more effective in those systems of automatic control that require speed of operation. It is connected with the fact that, in case when the gain compensator is used along with the decrease of the compensator gain, the operation speed of control systems reduces as the reduction of the compensator gain leads to the gain reduction of the open-loop transfer function, and, consequently, to a decreased operation speed. At the same time, the gain compensator allows providing a required ACS quality by approximately 2…2,5 time wider in range of parametrization of the control object.

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