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An adaptive control system for a shell-and-tube heat exchanger

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Abstract. This article suggests an adaptive control system for a hydrocarbon perspiration temperature control. This control system consists of a PI-controller and a pseudolinear compensating device that modifies control system dynamic properties. As a result, the behaviour research of the developed temperature control system has been undertaken. This article shows high effectiveness of the represented adaptive control system during changing control object parameters.

1. Introduction

Automatic control systems (ACS) with an unsteady control object must provide control device dynamic properties changing during control object properties alterations.

In most cases this is realized by changing a PID controller parameters. Such approaches are described in [1-5]. A control object identification or a special technique on a transient process are required during the use of these methods. These approaches are quite difficult and require a considerable time for a controller tune.

There is a less common but effective approach based on a special adaptive compensating device that is cascaded to a controller. This device changes control system properties and compensates control object properties [6, 7].

2. Approach

This article represents ACS research results of hydrocarbon perspiration temperature. This control system has been installed at Tomskneftehim Ltd. on an ethylene production line. The developed ACS consists of a PI controller and a pseudolinear compensating device that modifies control system dynamic properties with an amplitude suppression [7-11].

The proposed adaptation method does not change initial controller parameters during the control system operation. Indeed, it changes a compensating devices time constant depending on control object parameters changings. This changing happen in case of a low process quality only as a result of a control object parameters changings or a disturbance influence. It allows providing the required system stability and improving the transient process quality.

Tomskneftehim Ltd. implements technological pyrogas cooling and drying processes at a gas separation plant. This separation plant is a complex facility due to a multicomponent input carbon mixture. Hereby, pyrogas is going to a separator where primary water and carbon condensate mixture separates. Then, the pyrogas is going through the first turbocharger level input, then it is going to the next separator level through a refrigerator. This cycle repeats 5 times and the obtained cooled and drained pyrogas is going to the primary methane column that is required for a mixture of methane and hydrogen of primary purification. The heavy liquid fuel that is left in the separator is going to a shell-and-tube heat exchanger where it heats up to 90 Celsius degrees and is pumped out to a storehouse.

The current technological process uses a heat exchanger with a changing physical state of a matter. It has a transfer function as shown below:

$$W(s)=\left(\frac{K}{T_1\cdot s+1}\right)\left(\frac{1-b\cdot e^{-\tau\cdot s}}{(T_2\cdot s+1)(T_3\cdot s+1)}\right)\left(\frac{1}{T_4\cdot s+1}\right),$$

where K is a heat exchanger static transfer coefficient, T_i are heat exchanger time constants, b is a heat exchanger special constructive constant, τ is a heat exchanger lag constant.

The T_1 heat exchanger time constant determines the change of steam shell side pressure, the T_2 and the T_3 heat exchanger time constants take into consideration heat exchangers side and liquid properties changings into a heat exchanger tubes. The T_4 heat exchanger constant defines the output camera lag.

The investigated control system of a carbon hydrogen condensate has a shell-and-tube heat exchanger with a transfer function given below:

$$W(s)=\left(\frac{9}{0,27\cdot s+1}\right)\cdot\left(\frac{1-0,7\cdot e^{-10\cdot s}}{(25,8\cdot s+1)(0,94\cdot s+1)}\right)\cdot\left(\frac{1}{1,11\cdot s+1}\right).$$

The ACS has to maintain the temperature of the carbon hydrogen condensate at 90 degrees Celsius.

The heat exchanger as a control object has a significant lag. This lag should be taken into consideration when choosing a control system law. The required transient process quality for this ACS is an overshoot below 20% and a regulation time is less than 60 seconds.

The authors suggest a single-circuit ACS with a PI controller considering the control object mathematical model.

PI controller parameters that fulfil represented requirements have been calculated using the extended frequency response method and it has values K_p=0,2 and K_i=0,05.

Figure 1 represents the automatic hydrocarbon condensate temperature of the control system that has been created using MatLab 6.5 (Simulink).

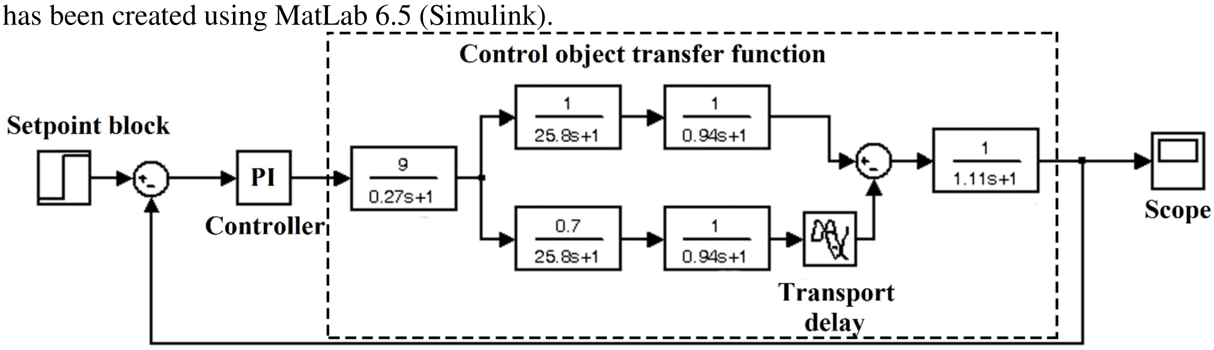

Figure 1. The automatic hydrocarbon condensate temperature of the control system model.

Control object internal disturbances are the heat transfer coefficient of external and internal tube surfaces and the tube specific thermal capacity. The main outer disturbances are the heat transfer agent temperature and the environment temperature. The T_2 and T_3 coefficients consists of these disturbances. The tube heat exchanger or liquid specific thermal capacity decrease leads to a decrease of T_2 and T_3.

Let is consider a case when the specific thermal capacity of the tube heat exchanger decreases so much that the T_2 coefficient decreases from 25,8 to 17,0 s.

Figure 2 represents the transient processes of the automatic hydrocarbon condensate temperature of the control system with T_2=25,8 s (figure 2a) and T_2=17,0 s (figure 2b).

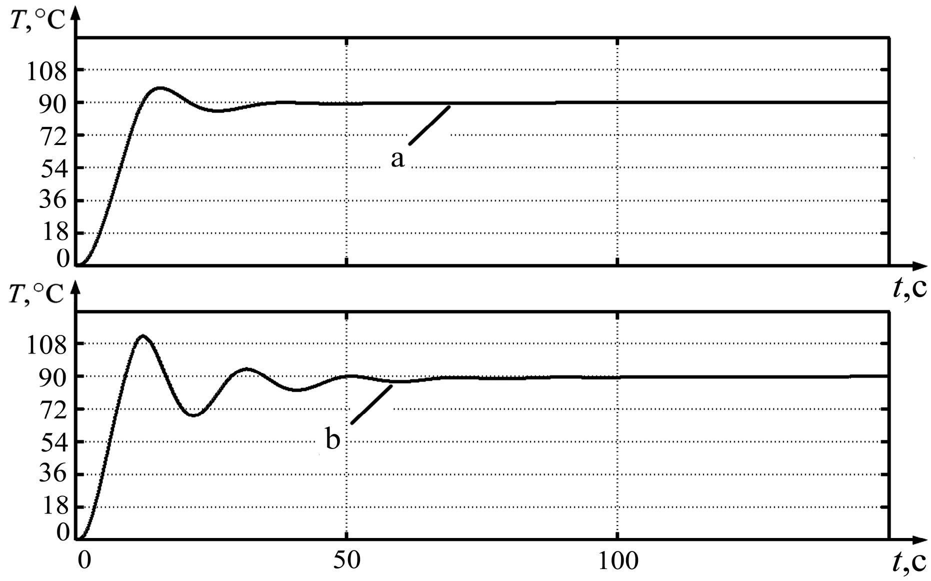

Figure 2. Automatic hydrocarbon condensate temperature of control system transient processes.

The ACS quality may become unsatisfactory as a result of uncontrolled control object disturbances and control object unsteadiness. In this case, the controller is unable to provide the required control quality and the system may become unsteady. This may cause a defective output production and a fire and explosive risk.

To improve the ACS quality and decrease an uncontrolled control object disturbances and a control object unsteadiness influence, it is suggested to use pseudolinear adaptive compensating device (PACD) with amplitude suppression. This device increases an amplitude stability margin when changing control object parameters.

Figure 3 represents an ACS with PACD and a structural scheme of amplitude suppression, where g – ACS setpoint; ε, ε_1 – PACD input and output signals; u – manipulated variable; y – control object output; PACD – PACD with amplitude suppression; TB – PACD tuning block; SQAB – system quality analyse block; TSG – test signal generator block; z – disturbance; q – parameter that characterizes control object unsteadiness; T – control object time constant; I – ACS quality criteria; S_1 and S_2 – start and stop TSG signals.

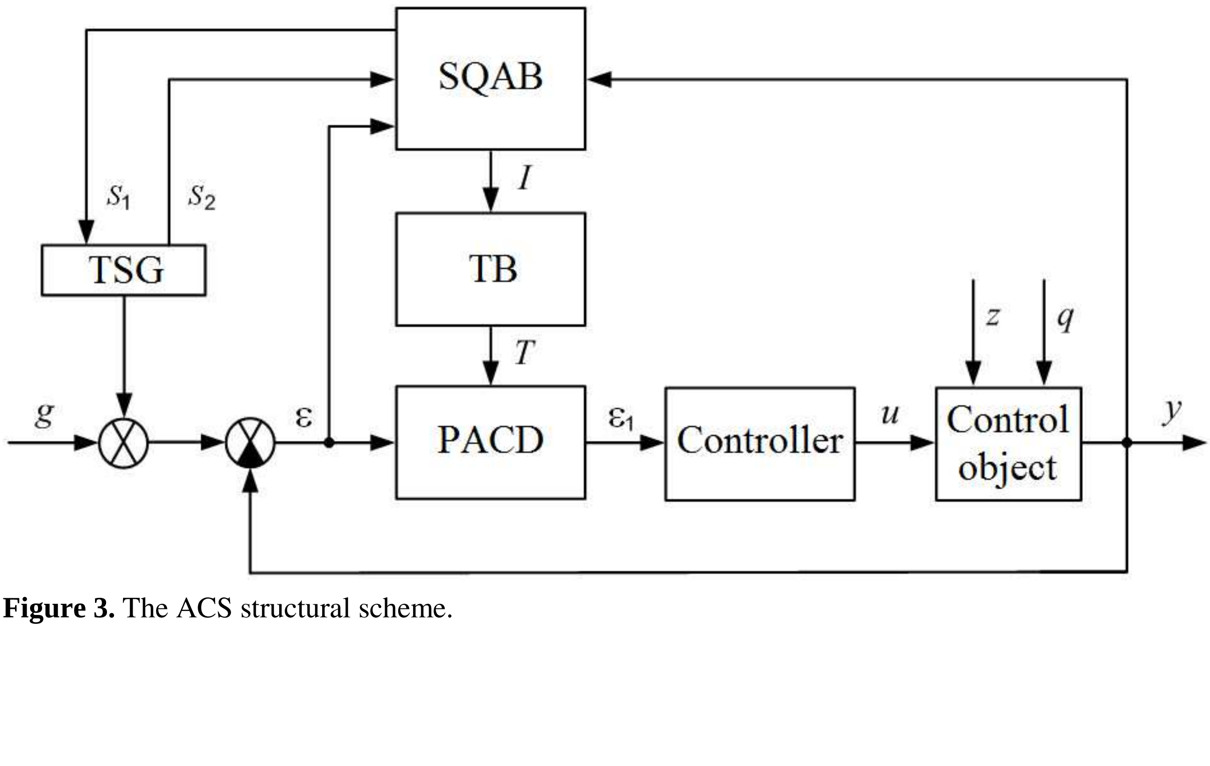

Figure 3. The ACS structural scheme.

The proposed adaptation method does not change initial controller parameters during the ACS activity. Indeed, it changes the compensating devices time constant depending on the change of control object parameters. An amplitude stability margin is changed by a compensator depending on the change of control object parameters during the process. These changings are made only in case of an unsatisfactory transient process quality. This quality degradation can be caused by the change of control object parameters or disturbance influence. It allows providing the ACS stability and improving the ACS quality.

The adaptive ACS processes are as follows. The TSG generates a test rectangular signal at the ACS start. The amplitude of this signal is equal to 1/10 of the setpoint and the duration is equal to 175 s. The SQAB calculates the ACS quality criteria value during the test impulse. The quality criteria are calculated using formulae given below:

$$I_1 = \int_{t_1}^{t_2} |\varepsilon(t)| dt,$$

where ε is an ACS error.

The calculated value is saved in the TB as a reference value. Further, the TSG will generate again the test signal after a specific time, the SQAB will calculate the quality criteria value and it will compare it value to the reference value. If condition $|I_t - I_0| > \Delta,$ where I_t is a current value and I_0 is the reference value is not met, then the adaptive controller should be tuned. The Δ value is an ACS quality tolerance.

If the tune decision has been made, then the TB calculates the compensating device time constant T and transfers it to the CD where it stores. This constant is calculated using the gradient method by formulae shown below:

$T_i = T_{i-1} + \Delta T$, where T_i, T_{i-1} are time constants at the current and previous steps; ΔT is a time constant increment value.

The time constant range of the compensating device is calculated with regard to required ACS transient process quality.

The ACS and PACD with the amplitude suppression model for the shell-and-tube heat exchanger has been created for its investigation and is represented in figure 4.

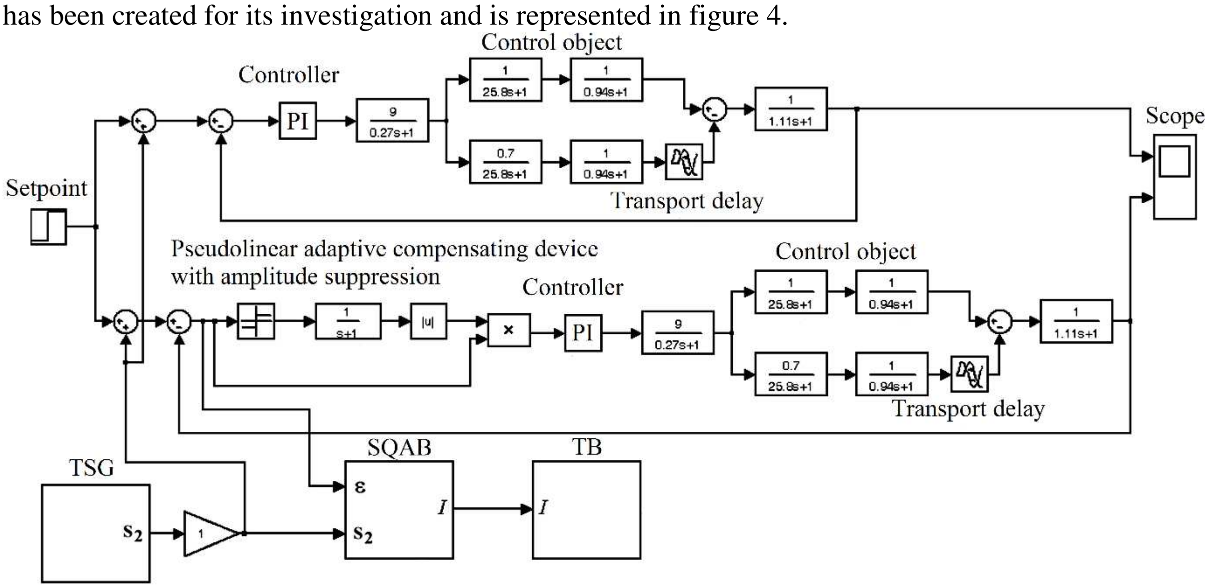

Figure 4. The ACS with PACD with amplitude suppression model for the shell-and-tube heat exchanger.

The initial PI controller parameters have been set as those calculated above and remain unchanged during the whole process.

Constant value T of the initial time has been taken to equal 0,01 s. This value has been taken in order to make minimal ACS frequency characteristics changes.

Changes of time constant T of the compensating device is performed by the TB using an S-function apparatus. The start of TSG is also performed by the SQAB using the S-function apparatus.

Figure 5 shows transient process graphs with a PI controller (figure 5a) and a controller with PACD with amplitude suppression (figure 5b). These graphs represent the adaptation ability of the ACS with a compensating device during control object parameters change. Figure 5c shows signal from the TSG.

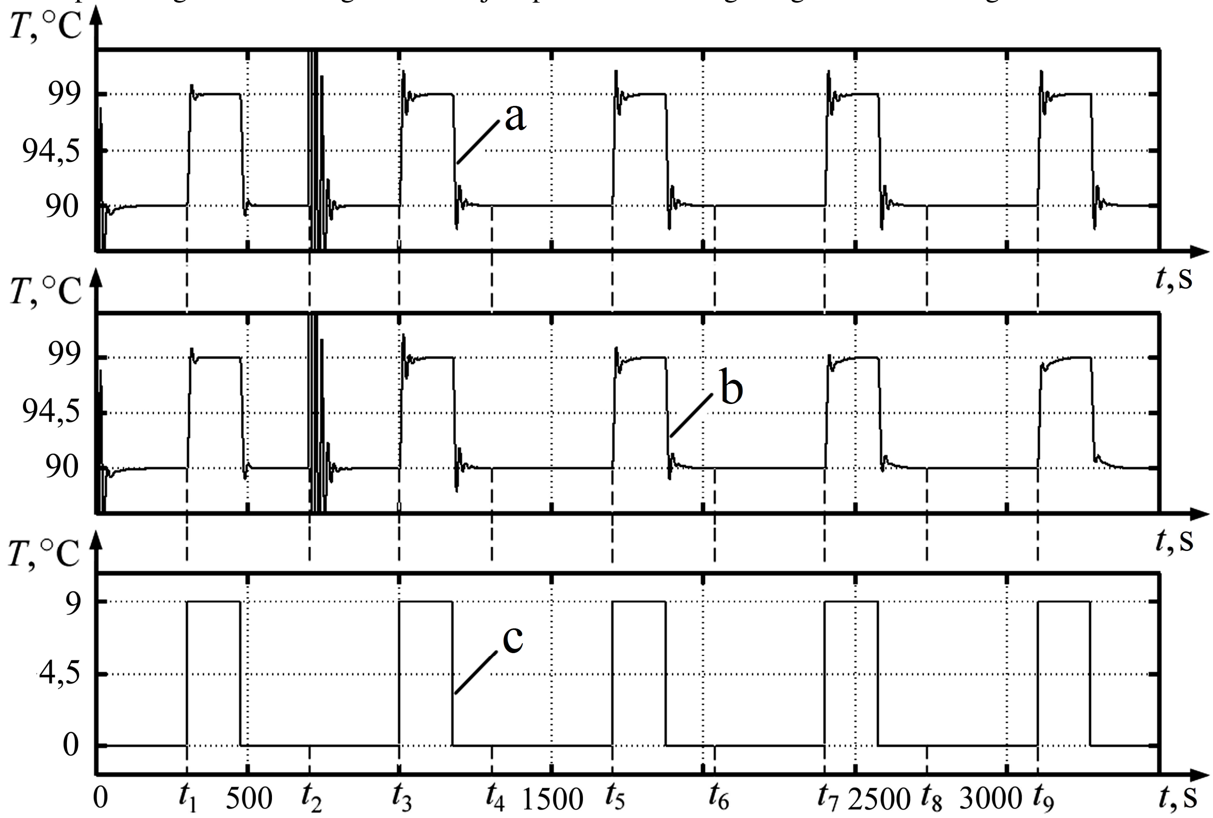

Figure 5. Transient process graphs.

These graphs have been made with the primary controllers tune to satisfy the transient process quality requirements that has been set above.

Also the compensating device tune has been set to T=0,01 s. This value has been taken in order to make minimal ACS frequency characteristics changes.

After ACSs start and the transient process decays, the TSG generates a test signal that proceeds to both ACSs at t_1 time moment (figure 5c). After this impulse, the SQAB calculates the ACS quality criteria value and saves it as the reference value. Then, at the t_2 time moment the T_2 control object time constant is changing from 25,8 to 17 s.

This changing makes the transient process more oscillated. These oscillations can be seen in figure 5 just after the TSG signal at the t_3 time moment. Then the SQAB calculates the transient process quality value and makes a decision that the compensating device has to be tuned. The compensating device time constant T is changed by the ΔT value at the t_4 time moment and saves this value at the compensating device.

Then, the TSG generates the rectangular test signal at the t_5 time moment and the compensating device tune continues. The quality criteria value of the transient process becomes satisfactory at the t_9 time moment, when the compensating device tuning is over.

The changing of the represented control object parameter caused three iterations of compensating device tune. The time constant of CD has become equal to 45 s after the tune.

The ACS with PACD shows the satisfactory transient process quality after the control object parameters changing. The ACS quality remains of high demand even for the control object parameter changing down to T_2=3 s, although the ACS without a corrector becomes unstable at T_2=8 s.

This paper investigates the a shell-and-tube heat exchanger properties of ACS during the change of the lag time of a control object. The results of this investigation show that the ACS and PACD with amplitude suppression remain stable even after increasing the lag time from 10 to 150 s. Incidentally, the ACS without the compensating device loses stability even at 28 s of lag time.

3. Conclusion

1. The adaptive ACS for the hydrocarbon condensate temperature has been proposed. This ACS includes the PI controller and the cascaded PACD.
2. The adaptive ACS shows its effectiveness during changing the control object parameters.
3. The adaptive ACS allows realizing a control system for a control object with unsteady parameters. This compensating device, based on microprocessors, can be added to a functioning ACS without extra hardware cost.

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