Adaptive Identification of Control Objects in Systems with Standard Controllers

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Abstract. The report is devoted to the study of the problem of parametric identification of controlled dynamic systems in their normal operation mode using a model with adjustable parameters. The task of determining parameters of test signals providing the specified accuracy of identification is considered. The peculiarity of the work consists in imparting adaptive properties to the identification procedure, which makes it possible to minimize the negative effect of "swinging" of the controlled object on its output when special test signals are applied.

Introduction
For many technological processes (TP) (aging of catalysts in chemical technology, wear of grinding bodies in grinding units, change in the coating layer in rotary kilns), the parameters of the models change in an uncontrolled manner over time over a wide range. This leads to the need for the current identification of control objects (CO) in order to restructure the parameters of the controllers [1–8]. Regulatory controllers from leading companies are equipped with control objects identification and self-tuning functions [9, 10], but these functions are not widely used in practice. The main reason is the difficulty of determining the rational parameters of the identification system for the personnel serving the automation equipment. The prospect of solving the problem is to develop reliable methods for automatic calculation of the parameters of identification systems. Taking into account modern trends, such methods can be oriented towards the use of computer simulation and numerical optimization. This study is based on the identification method using adaptive models in a variant that does not require the disabling of the regulator [11]. This method has, however, been tested for operability mostly in relation to servo systems, where the set value of the output variable is continuously changing. At the same time, most TPs require stabilization systems.

1. Identification by the method of adaptive model
A block diagram of an identification system with a tunable model is shown in Fig. 1.

The essence of the method lies in the fact that along the control channel, in addition to the actions from the controller $u_{reg}(t)$, test actions $\lambda(t)$ are also applied to the object. At the same time, the same influences are fed to the input of a closed-loop system model, which includes a control object and a regulator designed to maintain the output at level $y^*$. Comparing the monitored output of a real object $y(t)$ with the output of a model object $\hat{y}(t)$, the model is adjusted so as to minimize the difference between the two indicated signals, the measure of which can be the integral indicator.
\[ J_{id} = M \left\{ \int_0^{T_d} |y(t) - \hat{y}(t)| dt \right\}, \]

where \( M \) is the designation of the mathematical expectation.

Fig. 1. Identity scheme with adaptive model

The task is to determine such parameters of the algorithm for the formation of test and stabilizing effects, which during the identification period (that is, for \( t \in [0, T_{id}] \)) minimize the "harm" from the "swinging" of the control object,

\[ J_{st} = M \left\{ \int_0^{T_d} |y(t) - y^*| dt \right\}, \]

ensuring at the same time acceptable accuracy of identification of its model.

2. **Formalized statement of the problem of optimization of identification parameters**

The values of the integral indicator of identification accuracy \( J_{ub} \) and the integral indicator of stability are determined by a set of parameters:

- control object \( a_{ob} \),
- adaptive model of the control object \( a_{mod} \),
- control algorithm \( a_{reg} \),
- identification test influences \( a_{id} \),
- probabilistic characteristics of uncontrolled disturbing influences \( a_{pert} \).
The dependences \( J_{id} = \varphi_{id}(a_{ob}, a_{mod}, a_{reg}, a_{id}, a_{pert}) \) and \( J_{st} = \varphi_{st}(a_{ob}, a_{reg}, a_{id}, a_{pert}) \) are complex and in most cases cannot be obtained analytically. Using the introduced designations, the identification problem is to determine \( a^*_{sol} = \arg\min_{a_{sol}} \varphi_{id}(a_{ob}, a_{mod}, a_{reg}, a_{id}, a_{pert}) \). The problem of minimizing the "harm" from identification, provided that the required determination accuracy \( a_{ob} \) is achieved for any \( a_{ob} \in G_{ob} \) and any \( a_{pert} \in G_{pert} \) (where \( G_{ob} \) and \( G_{pert} \) are the ranges of possible values of the CO parameters and disturbances), is formulated as the determination of the parameters \( a^*_{reg}, a^*_{id} \) by solving the problem of finding

\[
J^*_{st} = \min_{a_{id}, a_{reg}} \max_{a_{ob}, a_{pert}} \varphi_{st}(a_{ob}, a_{reg}, a_{id}, a_{pert})
\]

with restrictions

\[
P(\delta_{id} \leq \delta_{id}) \geq \gamma_{id}, P\left[\left|y(t) - y^*\right| \leq \Delta\right] \geq \gamma_{st}.
\]

Vector probabilistic constraints on the maximum value of the relative identification errors are a set of scalar constraints of the form \( P(\delta_{id,j} \leq \delta_{id,j}) \geq \gamma_{id,j} \) for all components of the vector \( a_{ob} \), moreover, \( \delta_{id,j} = \left|\left(a^*_{ob,j} - a_{ob,j}\right) / a_{ob,j}\right| \), and parameters \( \gamma_{id,j} \), close to 1, determine the admissible risks of violation of the constraints. The scalar constraint requires that, with a sufficiently high probability \( \gamma_{st} \), the output variable \( y(t) \) deviates from the given value \( y^* \) by no more than \( \Delta \).

Two approaches to solving the formulated problem were considered. In the first option, \( a^*_{id} = \text{const}(t) \), and the parameters of identifying influences \( \lambda(t) \) are calculated in advance before the start of the process of identifying the CO based on the available a priori information about the CO and disturbances. Since this solution must provide the required identification accuracy for any \( a_{ob} \in G_{ob} \) and \( a_{pert} \in G_{pert} \), it is appropriate to call such a method robust identification. In the second variant, \( a^*_{id} \neq \text{const}(t) \), and the parameters of test influences \( \lambda(t) \) are formed not in advance, but in the process of identification itself, that is, using the feedback principle. It is appropriate to call this method adaptive identification.

Taking into account that many technological processes are inertial processes with delay and self-leveling, the formulated problem was considered using the example of a CO, the model of which corresponds to a first-order inertial link with delay. During the operation of the technological processes, the system must maintain the output variable \( y(t) \) at a given level \( y^* \) under the conditions of uncontrolled disturbances \( n(t) \) reduced to the output of the CO.

In this case, the transfer functions of the CO model and a typical proportional-integral controller are given by the expressions

\[
H(p) = Ke^{-pT} / (Tp + 1)
\]

and

\[
W(p) = k_p + k_i / p,
\]

and the corresponding parameter vectors have the form \( a_{ob} = [K,T,\tau]^T \) and \( a_{reg} = [k_p,k_i]^T \).

Let the domain \( 0 \) be given by the inequalities

\[
\underline{K} \leq K \leq \overline{K}, \quad \underline{T} \leq T \leq \overline{T}, \quad \underline{\tau} \leq \tau \leq \overline{\tau}.
\]

For uncontrolled disturbances, we will accept the widespread model of a random process formed by passing continuous white noise of unit intensity \( \xi(t) \) through an inertial link, so that
\[ n = \frac{c}{(R_p + 1)\xi} \]
and \( a_{\text{pert}} = [c,R]^T \). The parameters \( c \) and \( R \), which determine the amplitude and smoothness of the disturbances, are assumed to be known up to the intervals \( \xi \leq c \leq \overline{c}, \quad R \leq R \leq \overline{R} \).

These inequalities define the region \( G_{\text{pert}} \). In order to approximate the methods used in practice [1], a sequence of "stepwise" test actions alternating in sign is considered
\[ \lambda(t) = \hat{\lambda} \operatorname{sgn}[\sin(\pi t / T_i)] \]
with amplitude \( \lambda \) and duration \( T_i \). Thus, \( a_{id} = [\lambda,T_i,N]^T \), where \( N \) is the number of "steps" (see Fig. 2).

![Fig. 2. "Stepwise" test influences](image)

### 3. Robust identification

The robust identification algorithm, proposed as suboptimal and investigated by computer simulation in Matlab-Simulink, provides for the use of so-called “robust” settings of the controller \( a_{\text{reg}}^* = a_{\text{reg}}^{(\text{rob})} \) for control during the identification period, that is, settings that provide an acceptable quality of control for any possible parameters of CO \( a_{ob} \in G_{ob} \). On the one hand, the use of such a controller is motivated by the fact that in the absence of data on the real parameters of the CO (and they appear only as a result of identification), robust settings can protect the "object-controller" system from instability and unacceptable decrease in the level of stability of the output variable in conditions of uncontrolled random disturbances. On the other hand, a "weak" robustly configured regulator will not be able to significantly weaken the response of the CO to test effects. In the general case, finding the robust settings of controllers is a complex independent task, the consideration of which is beyond the scope of this article. Nevertheless, for system (1), (2), a simple solution can be proposed. In [12], it was shown that for a CO of type (1), settings of controller (2) close to optimal by the criterion \( \min J_{st} \) can be found by the formulas
\[ a_{\text{reg}} = [k_p = k_i, k_i = 0.589 / K_T]^T. \]
Then the controller can be used as a robust one
\[ a_{\text{reg}}^{(\text{rob})} = [k_p^{(\text{rob})} = k_i T, k_i^{(\text{rob})} = 0.589 / K_T]^T. \]
Providing suboptimal settings for \( \mathbf{a}_{ob} = [\bar{K}, T, \bar{\tau}]^T \), controller (5) has weakened settings for all other op amps from area (3). This ensures stability, and hence the performance of the system with all possible combinations of CO parameters. At the same time, rather weak settings of the regulator distort the influence of test influences to the least extent during the identification period.

We will assume that the identification accuracy is specified, which is characterized by a relative error

\[
\delta_K = \frac{K - \hat{K}}{K}, \quad \delta_T = \frac{T - \hat{T}}{T}, \quad \delta_{\tau} = \frac{\tau - \hat{\tau}}{\tau}.
\]

Then the problem of minimizing the deviations of the output variable from a given value under constraints on the identification error is reduced to determining

\[
\min_{\lambda, T, \bar{\tau}, \bar{K}, \hat{K}, T^0, T^1} \max_{\omega \in \mathbb{R}} M \left\{ \int_0^{T^0} \left| y(t) \right| dt \leq \delta_K, \omega \sigma_{\delta_k} \leq \bar{\delta}_K, \omega \sigma_{\delta_T} \leq \bar{\delta}_T, \omega \sigma_{\delta_{\tau}} \leq \bar{\delta}_{\tau}, \omega \sigma_y \leq \Delta \right\},
\]  \tag{6}

where \( \sigma \) – standard deviation (RMS) designation and parameter \( \omega \) is determined by the acceptable risk of violation of the identification accuracy boundaries and is usually in the range from 2 to 3.

The exact solution of problem (6) seems to be rather complicated due to a significant number of parameters \( K, T, \bar{\tau}, \lambda, T^0, T^1, N, C, R \); therefore, for an approximate solution, modeling in the Matlab-Simulink software environment was used. The simulation model of the identification system is shown in Fig. 3. Fragments of simulation of the system "CO - Regulator - Adaptive CO model" are shown in Fig. 4 and 5.

![Simulink model of an identity system with adaptive model](image)

Fig. 3. Simulink model of an identity system with adaptive model

In the non-adaptive version, the identification parameters \( \lambda, T^0, N \) are determined by analytical and numerical (simulation) calculations prior to the start of identification without using current
information about the identified object. In this case, it is proposed to count on the worst and consider the one shown in Fig. 6 system. It corresponds to the greatest “harm” when applying the test actions necessary to achieve the required accuracy of identification of the CO model in a closed robustly tuned PI controller system. Indeed, the minimum value of the gain leads to the need to increase the amplitude of the test influences \( \lambda \). The maximum values of the dynamic parameters \( T \) and \( \tau \) force to increase the duration of the test impacts \( T_{\lambda} \). The choice of the limiting values of the parameters of the perturbation model \( \bar{c} \) and \( R \) leads to a maximum increase in the intensity of the "residual" disturbances \( n_{res} \). This, in turn, is equivalent to the maximum amplification of the measurement noise and leads to the need to increase the number of test influences \( N \).

Fig. 4. Test influences and reaction to them of the controlled object

Fig. 5. Identification error module at the beginning and at the end of the identification process

Fig. 6. Block diagram of the system for calculating the parameters of test influences

The robust identification procedure includes the following steps.
1. Calculation of the parameters of a robust controller according to the formula (5).
2. Determination of the strongest "residual" disturbances by means of simulation modeling of the RMS, that is, the deviations of the output variable from the task in the system with the most difficult-to-identify CO, which is controlled by a robust PI controller.

3. Calculation of the amplitude of test influences

\[ \lambda = (\Delta - \rho \sigma_{\text{res}}) / K, \]  

(7)

4. Calculation of the duration of the "steps" sufficient to reveal the reaction of the CO to the test influences: \( T_\lambda = \bar{T} + 3\bar{T}. \)

5. Finding, using statistical simulation, the number of "steps" \( N \) required to achieve the required identification accuracy \( \bar{\delta}_{id} \) in the system shown in Fig. 6, when applying test influences (4) with the parameters determined at stages 3 and 4.

4. Two-step adaptive identification procedure

1. Before the start of identification, the behavior of the CO is observed for some time in a control system with a robust controller \( a^{(\text{rob})} \), and statistically, not extreme, but real probabilistic characteristics of residual disturbances \( n_{\text{res}} \) (t) are determined. This allows, when calculating by formula (7), increasing the amplitude of "swinging" influences \( \lambda \) without taking the output variable \( y(t) \) beyond the permissible limits.

2. At the initial stage, a rough identification is performed, when the parameters \( a_{id}^{(\text{first})} \) are determined according to the scheme considered above with less stringent requirements for the accuracy of estimating the parameters of the CO \( \bar{\delta}_{id}^{(\text{first})} \geq \bar{\delta}_{id} \) model. This makes it possible to obtain rough estimates of the CO \( a^{(\text{first})} \) parameters in a relatively short time by supplying a sufficiently small number \( N^{(\text{first})} \) of oscillating CO test influences.

3. Obtaining rough estimates \( a_{id}^{(\text{first})} \) allows one to reduce the size of the initial uncertainty region \( G_{ab} \) to a smaller value \( G_{ab}^{(\text{first})} \subseteq G_{ab} \). This makes it possible, before the second (final) stage, by implementing the calculations according to items 3, 4, 5 of the robust identification procedure, to determine the parameters of the final series \( a_{id}^{(\text{clus})} = [\lambda^{(\text{clus})}, T_\lambda^{(\text{clus})}, N^{(\text{clus})}]^T \) that ensure the achievement of the specified identification accuracy \( \bar{\delta}_{id} \) at significantly lower values of the vector components \( a_{id}^{(\text{clus})} \) than at the initial stage.

As a result, as simulation modeling shows, adaptive identification with the same accuracy in estimating the parameters of the CO model is accompanied by significantly less CO “swinging” than robust identification. Formally, this is expressed by the inequality

\[ J^{(\text{rob})}_{st} \gg J^{(\text{adapt})}_{st} = J^{(\text{first})}_{st} + J^{(\text{clus})}_{st}. \]

Identification of an inertialess control object. Let us explain the difference between the two considered approaches to identification using a relatively simple example of an inertialess control object. Its model in deviations from the given mode has the form \( \Delta y(t) = K \cdot \Delta u(t) + n(t) \), where \( K \) is a positive gain to be identified, about which it is only known that \( 0 \leq K \leq \bar{K} \) and \( n(t) \) are uncontrollable disturbances. As previously said \( \Delta u(t) = \Delta u_{\text{reg}}(t) + \lambda(t) \), so the deviation of the output variable from the set value is \( \Delta y(t) = K\lambda(t) + n_{\text{reg}}(t) \). Let us assume that during identification a sufficiently “weak” regulator is used, which does not suppress artificial disturbances \( \lambda(t) \), but only
removes relatively low-frequency components \( n(t) \). Then \( n_{\text{exc}}(t) = K\Delta u_{\text{reg}}(t) + n(t) \) does not depend on \( \lambda(t) \) and represents “residual” disturbances, that is, that part of disturbances \( n(t) \) that the controller could not suppress. Let us assume that the control of the output variable \( y(t) \) is performed at discrete times with a period \( T \). In this case, \( \Delta y_i = \Delta y(iT) , i = 1,2,...,N \) becomes known. An estimate of the unknown gain of CO \( \hat{K} \) can be found using the least squares method from the condition

\[
J = \sum_{i=1}^{N} (\Delta y_i - \hat{K}_i \lambda_i)^2 \rightarrow \min.
\]

In this case, as is easy to show, the estimation error is \( \Delta K = K - \hat{K} = -\left(\sum_{i=1}^{N} n_{\text{exc},i} \lambda_i / \sum_{i=1}^{N} \lambda_i^2\right) \), where the designations are introduced \( n_{\text{exc},i} = n_{\text{reg},i}(iT), \lambda_i = \lambda(iT) \). From here, you can get the ratio for calculating the standard deviation (RMS) of the estimate from the exact value \( \sigma_{\Delta K} = \sigma_{n_{\text{res}}} / (\sqrt{N} \lambda) \).

The deviation of the output variable from the set value caused by the test influences has a value at each moment of time \( t \), and the measure of the instability of behavior \( K\lambda(t) \) caused by the “swinging” CO influences \( y(t) \) can be considered \( W = \int_{0}^{T} |K\lambda(t)| dt \). The problem of optimization of the identification parameters is to calculate such \( T, \lambda \) and \( N \) so that the instability index \( W \) takes a minimum value. When solving this problem, it is necessary to take into account that the deviation of the output variable from the task with a sufficiently high probability should not exceed the threshold value \( \Delta Y \) in absolute value, which is equivalent to condition \( K\lambda + \omega\sigma_{n_{\text{res}}} \leq \Delta Y \). Here the parameter \( \omega \) depends on the admissible risk of violation of constraints and is usually in the range from 2 to 3. The requirement to ensure sufficient identification accuracy for solving control problems, that is, a sufficiently small relative estimation error \( \delta K = \left|K - \hat{K}\right| / K \), should also be taken into account. This is formalized by the condition \( \sigma_{n_{\text{res}}} / (\sqrt{N} \lambda K) \leq \delta K / \sigma_{\delta K} \), where \( \sigma_{\delta K} \) is the maximum permissible standard deviation of the identification error. And, finally, since for qualitative identification it is necessary that the measurement noises do not have autocorrelation, then the condition \( T \geq T_{\text{cor}} \) must be satisfied, where \( T_{\text{cor}} \) is the decay time of the correlation function of the signal \( n_{\text{reg}}(t) \).

First, let us consider the solution of the problem under conditions when the specified identification parameters are determined only once “counting on the worst”. In this option, \( W = T N K \lambda \). Taking into account that the constraints formulated above must be satisfied for any possible values of the parameters \( K, \sigma_{n_{\text{res}}} \) and \( T_{\text{cor}} \), we arrive at the problem of determining \( \min \{TN\lambda / T \geq T_{\text{cor}}, \lambda \leq (\Delta Y - \omega\sigma_{n_{\text{res}}}) / K, N \geq \text{Ent}\left\{\frac{\sigma_{n_{\text{res}}} / (\sigma_{\delta K} K \lambda)}{\sigma_{\delta K} (\sigma_{\delta K} K \lambda)}\right\} + 1\} \), where the limiting values of the characteristics of residual disturbances \( \sigma_{n_{\text{res}}} \) and \( T_{\text{cor}} \) are determined from the operation data of the considered or similar CO. The solution to the formulated optimization problem has the form: \( T = T_{\text{cor}}, \lambda = (\Delta Y - \omega\sigma_{n_{\text{res}}}) / K, N = \text{Ent}\left\{\frac{\sigma_{n_{\text{res}}} / (\sigma_{\delta K} K \lambda)}{\sigma_{\delta K} (\sigma_{\delta K} K \lambda)}\right\} + 1 \).

Let us give a numerical example, assuming the following parameter values:

\[
K = 1, \quad K = 5, \quad K = 3, \quad \sigma_{n_{\text{res}}} = 0.5, \quad T_{\text{cor}} = 0.84, \quad \omega = 2, \quad \sigma_{\delta K} = 0.1, \quad \Delta Y = 3.
\]
Consider further an alternative adaptive identification procedure.

1. At the first preliminary stage, the operation of a CO closed by a sufficiently "weak" regulator is passively observed, which eliminates relatively low-frequency components and according to the observation data for the output variable, the current values of the RMS $\sigma_{n_{ws}}$ and decay time $T_{\text{corr}}$ of the correlation function of residual disturbances are statistically estimated.

2. At the second stage, from the condition of ensuring the conditions of rough identification $\tilde{\sigma}_{\Delta K} > \sigma_{\Delta K}$, the parameters of the initial series of test actions are determined

$$T^{(\text{first})} = T_{\text{corr}}, \quad \lambda^{(\text{first})} = (\Delta Y - \omega \sigma_{n_{ws}}) / K, \quad N^{(\text{first})} = \text{Ent}\{[\sigma_{n_{ws}} / (\sigma_{\Delta K}^{(\text{first})} K \lambda^{(\text{first})})]^2\} + 1$$

and the initial series of such actions with the calculated parameters is realized. Let, at the end of the initial series, an estimate of the amplification factor of CO $\hat{K}^{(\text{first})}$ be obtained. The standard deviation of the error of this estimate is $\tilde{\sigma}_{\Delta K}^{(\text{first})} = \sigma_{n_{ws}} / (\sqrt{N^{(\text{first})}} \cdot \lambda^{(\text{first})})$, and the new reduced uncertainty zone can be estimated using the formulas $K^{(\text{first})} = \hat{K}^{(\text{first})} + \omega \sigma_{\Delta K}^{(\text{first})}$, $K^{(\text{first})} = \hat{K}^{(\text{first})} - \omega \sigma_{\Delta K}^{(\text{first})}$. Then the standard deviation of the maximum relative identification error after its initial stage is $\tilde{\sigma}_{\Delta K_{\text{new}}}^{(\text{first})} = \tilde{\sigma}_{\Delta K}^{(\text{first})} / K^{(\text{first})}$.

3. If $\sigma_{\Delta K_{\text{new}}}^{(\text{first})} \leq \sigma_{\Delta K}$, then the identification process ends, otherwise the second (final) series of identification actions is performed, for which its parameters are preliminarily determined

$$T^{(\text{final})} = T_{\text{corr}}, \quad \lambda^{(\text{final})} = (\Delta Y - \omega \sigma_{n_{ws}}) / K^{(\text{first})}, \quad N^{(\text{final})} = \text{Ent}\{[\sigma_{n_{ws}} / (\sigma_{\Delta K} K^{(\text{first})} \lambda^{(\text{final})})]^2\} + 1$$

The final value of the instability index for adaptive identification

$$W = \int_{0}^{T^{(\text{final})}} [K \lambda(t)] dt = K \left( T^{(\text{first})}_\lambda N^{(\text{first})} \lambda^{(\text{first})} + T^{(\text{final})}_\lambda N^{(\text{final})} \lambda^{(\text{final})} \right)$$

Let us give a numerical example related to the same CO that was considered earlier, in an adaptive version. Suppose additionally that at the first preliminary stage of adaptive identification data on residual disturbances $\sigma_{n_{ws}} = 0.2$ and $T_{\text{corr}} = 0.54$ were obtained. Then, accepting $\tilde{\sigma}_{\Delta K}^{(\text{first})} = 0.25$, for the initial series we obtain $T^{(\text{first})} = 0.54$, $\lambda^{(\text{first})} = (3 - 2 \cdot 0.2) / 5 = 0.52$, $N^{(\text{first})} = \text{Ent}\{[0.2 / (0.25 - 0.52)]^2\} + 1 = 3$ or taking into account the requirement for the parity of the number of "steps" in the series $N^{(\text{first})} = 4$. Suppose that at the end of the initial series, an estimate of the amplification factor $\hat{K}^{(\text{first})} = 2.8$ of the OA is obtained. Then $\sigma_{\Delta K}^{(\text{first})} = 0.2 / (\sqrt{4} - 0.52) = 0.19$, $\tilde{\sigma}_{\Delta K}^{(\text{first})} = 2.8 + 2 \cdot 0.19 = 3.18$, $\tilde{\sigma}_{\Delta K}^{(\text{first})} = 2.8 - 2 \cdot 0.19 = 2.42$, $\tilde{\sigma}_{\Delta K_{\text{new}}}^{(\text{first})} = 0.19 / 2.42 = 0.08$. Since $\sigma_{\Delta K_{\text{new}}}^{(\text{first})} \leq \sigma_{\Delta K}$, then the identification process can be completed at this point and $W = KT^{(\text{first})}_\lambda N^{(\text{first})} \lambda^{(\text{first})} = 3 \cdot 0.54 \cdot 4 \cdot 0.52 = 3.38$.

Comparison of W indicators shows a significant advantage of the considered adaptive approach to identification.

Let us now assume that a higher identification accuracy is required, that is, $\tilde{\sigma}_{\Delta K} = 0.05$ (and not 0.1). In this case, $\tilde{\sigma}_{\Delta K_{\text{new}}}^{(\text{first})} = 0.093 > \sigma_{\Delta K} = 0.05$, means that the identification must be continued. Let's define the parameters of the final identification cycle. In accordance with the previously obtained formulas
Thus, it is necessary to implement at least 5 more test "steps" with a length of 0.54 and a height of 0.82 each. In order that the test influences do not, on average, shift the output variable from the task, \( N \) must be even, therefore, we should set \( N^{(\text{clos})} = 6 \). The final value of the instability index caused by test influences during the identification period will be

\[
W = K(T^{(\text{clos})}_n N^{(\text{clos})} \lambda^{(\text{clos})} + T^{(\text{first})}_n N^{(\text{first})} \lambda^{(\text{first})}) = 3(0.54 \cdot 4 \cdot 0.52 + 0.54 \cdot 6 \cdot 0.82) = 11.34,
\]

which is significantly less than the value 159 obtained for non-adaptive identification with less stringent requirements for the accuracy of the CO gain estimate.

**Conclusion**

We have proposed a two-stage adaptive identification method in a closed-loop control system based on the idea of a tunable model. With regard to inertial objects with delay, a fully formalized algorithm for calculating the parameters of typical regulators and test control actions of the "step" type has been developed, which provides a given identification accuracy with minimal costs associated with the "swing" of the CO when applying test actions.

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