Algorithms for synthesis of control systems for dynamic objects based on the modal method

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Abstract. Algorithms for the synthesis of control systems for dynamic objects based on the modal method are given. Algorithms have been developed for determining the placement of poles in multidimensional systems with proportional-differential feedback on the output, providing the desired distributions on the complex plane of the eigenvalues of the matrix of a closed system. Algorithms for selecting feedback in control systems of dynamic objects are proposed, which allow for stable identification of the coefficients of the equations of the object and the observed values of the object used in the control device. Adaptive algorithms have been developed to place poles of non-minimal-phase stochastic systems in the presence of white noise at the output, which makes it possible to exclude the operation of matrix inversion, which requires significant computational costs. Adaptive control algorithms based on the modal method have been developed for dynamic objects with a delay under conditions of a priori uncertainty and unsteadiness of technological process parameters, providing exponential dissipativity of the control process. Based on the developed regular algorithms, an adaptive control system for the synthesis of ammonia is proposed.

1 Introduction

The emergence of new efficient technological processes and the intensification of existing ones place ever higher demands on their management systems. The efficiency of the production management system is largely determined by the quality of regulation and control of technological parameters [1-3]. This is because modern technological complexes and installations are characterized by stressful conditions of the processes occurring in them. At the same time, for the synthesis of control systems, as a rule, there is not enough complete a priori information about processes and it is not always possible to obtain it. Most control objects are complex dynamic systems with many degrees of freedom, subject to the action of many external and parametric disturbances; processes in these objects are relatively little studied, and work on their identification and control is fraught with great difficulties; working conditions are predictable with low probability. This is determined by the complexity of the processes, their dynamics, the impossibility of obtaining any sufficiently adequate mathematical description of them, the physical impossibility of direct measurement of all parameters necessary for effective control, as well as the influence of controlled and uncontrolled disturbances, the nature of which may also change during the technological process and the functioning of the control system. In such cases, it is necessary to resort to automatic control with adaptation, which allows for stable and efficient operation of the entire system as a whole [3-9]. To solve these issues, it is required to develop adaptive control systems for linear or linearizable multidimensional objects with modal control using discrete identifiers and with disturbance compensation, which can improve the quality of control by choosing the shortest duration and amplitude of the identification signal when the system is out of order. In this regard, it is very tempting to consider various possible approaches to solving problems of increasing the accuracy of calculating the states of dynamic systems based on modal methods and to identify the most promising for practical use methods and algorithms for solving ill-posed problems [9–15].

2 Objects and Methods

- Development of algorithms for the synthesis of control systems for dynamic objects based on modal methods.

Consider the problem of choosing from several observable quantities, such that the system has minimal complexity in order. The solution to this problem is obtained by the operator-polynomial method [13, 16, 17], which provides the possibility of choosing not only the poles but also the zeros of the system according to the setting and disturbing influences.

We will assume that the synthesized system consists of a control device and a given part [13,16], the equations of which have the form:

\[ A(p)y = B_0(p)u + B_1(p)f, \]  
\[ A(p)v = B_0(p)u + Z(p)f, i = (1, M). \]

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where \( y \) is a controlled quantity (not observed), \( u \) is control; \( f_i \) is an observed disturbance; \( \bar{v}_i \) is output quantities that can be observed, \( M \) is their number; \( A(p) \) is a proper operator \([2, 18] \); \( B(p) \), \( \bar{V}(p) \), \( \bar{Z}(p) \) – input operators of a given part, \( j = 0, 1; g – \) the setting effect; \( R(p) \), \( Q(p) \), \( L(p) \), \( Q(p) – \) some polynomials from \( p \); \( v_i – \) the observed magnitudes of the object, \( q – \) their number, \( q \leq M \).

Operators are polynomials from \( p = dt / d \), with constant coefficients, we will agree to denote the degree of the polynomial: \( n[A] = n, n[B_j] = m_j, n[\bar{V}_i] = \bar{n}_i, n[\bar{Z}_i] = \bar{s}_i \). Then in the equations (1), (2) \( m_j \leq n, \bar{n}_i = n, \bar{s}_i \leq n \). The magnitudes \( v_i \) are selected from the number of magnitudes \( \bar{v}_1, \bar{v}_2, \ldots, \bar{v}_t \), and after selection of them, as well as corresponding to the following polynomials according to (2), the polynomials \( \bar{V}_i(p) \) and \( \bar{Z}_i(p) \) are numbered so that \( n_{s,i} \leq n_i, i = (1, q - 1) \). The value is

\[
\mu_i = \min \left \{ r - r_j, r - t_j; j = 0, 1; i = \left (1, q - 1 \right ) \right \},
\]

where

\[
r_j = n[Q_j], l_i = n[L_i], r = n[R],
\]

are the indices of the control device.

Let us pose the problem of choosing the variables \( v_j \) included in equation (3), as well as the degrees and coefficients of the polynomials of this equation so that, with the minimum possible order of the control device, i.e. at \( r \to \min \), the following conditions were fulfilled:

\[
\mu_i \geq \mu^*_i, H(p) = H^*(p),
\]

where \( H(p) \) is the own operator of the synthesized system; \( H_i(p), H_j(p) \) are input operators of the system.

The polynomials of equation (3) under conditions (4) are determined by the solutions of the systems of the following algebraic equations \([12, 13] \):

\[
A(p)R(p) + \sum_{i=1}^{q} L_i(p)v_i(p) = H(p),
\]

\[
B(p)Q(p) = H_0(p),
\]

\[
B(p)Q(p) + B(p)R(p) + \sum_{i=1}^{q} L_i(p)C_i(p) = H_i(p)
\]

So polynomials \( R(p) \) and \( L_i(p), i = (1, q) \) are determined by the solution of the system:

\[
Gd = h
\]

where

\[
d = [\lambda_{p_0}, \ldots, \lambda_{p_q} \mid \lambda_{p_0}, \ldots, \lambda_{p_q} \mid \rho_{p_0}, \ldots, \rho_{p_q}]^T\]

\[
h = [\eta_1, \eta_2, \ldots, \eta_{m-p}]^T.
\]

Here \( \lambda_{p_0}, \rho_{p_0}, \eta_1 \) are the coefficients at \( p^i \) polynomials \( L_i(p), R(p), H^*(p) \) respectively; the matrix \( G \) is composed of coefficients \( \alpha_k \) and \( \nu_k \) with \( p^i \) polynomials \( A(p) \) and \( V_j(p), i = (1, q) \).

When finding a solution to equation (6), computational difficulties arise because when solving the equation, it is necessary to use regularization methods \([10, 11] \). When solving equation (6), we take the approximation conditions in the form \( \| h - \bar{h} \| \leq \delta \), where \( \bar{h} \) is the exact value of the right side of the equation. To regularize the solution of this equation, we will use the method of M.M. Lavrentiev \([10, 11] \):

\[
\alpha d + Gd = h,
\]

where \( \alpha > 0 \) is the regularization parameter; \( R_o = \theta_o(G) = (\alpha + G)^{-1} \) if conditions

\[
\lim_{\alpha \to 0} R_o Gd - d_{\alpha} = 0, \ d \perp \ker G, \ (6) \text{ are satisfied leads to a limited approximation of the problem} \[11\].

The solution of equation (7) can be expressed in the form:

\[
d_{\alpha} = (\alpha I + G)^{-1} h = \theta_{\alpha}(G)h,
\]

where \( \theta_{\alpha}(\lambda) \) is the generating system of functions \( \theta_{\alpha}(\lambda) = (\alpha + \lambda)^{-1}; \lambda \) – spectral parameter \( 0 \leq \lambda < \infty \); \( I \) is the identical operator; \( \langle (\alpha I + G)d, d \rangle > 0 \text{ \forall } d \in H \). Thus, problem (7) is correct.

When solving equation (6), one can also use the concepts of pseudo-inversion \([11, 19-21] \). In case \( Gd \neq h \), i.e. measure of inconsistency \( \mu_o = \inf \| Gd - h \| > 0, d \in D \| Gd - h \| = \mu_o \), the solutions of this equation do not converge at \( \alpha \to 0 \) to the pseudo solution \( d = G^* h \). In this case, it is advisable to use the following relation:

\[
d_{\alpha} = d_{\alpha} + \alpha \frac{d_{\alpha}}{d\alpha},
\]

where

\[
\frac{d_{\alpha}}{d\alpha} \text{ is the derivative of the element } z_{\alpha} \text{ as a function of the parameter } \alpha .
\]

Then one can write \([11] \):

\[
d_{\alpha} = (\alpha I + G)^2 Gz_{\alpha},
\]

i.e. \( d_{\alpha} \) is the solution of the equation regularized especially: \( (\alpha I + G)^2 d_{\alpha} = Gh \). Taking into account that in this case, the pseudo-solution \( d_{\alpha} \) satisfies the equation \( G^2 d_{\alpha} = Gh \) in the usual sense, we will have:

\[
d_{\alpha} = (\alpha I + G)^2 Gd_{\alpha} \text{ and } d_{\alpha} - d_{\alpha} = \alpha (\alpha I + G^2) d_{\alpha}
\]

Then, following \([10,11] \), we can show the validity of the following limit relation:

\[
\lim_{\alpha \to 0} d_{\alpha} - d_{\alpha} = 0, \ i.e. \text{ the considered method is regularizing.}
\]

The above expressions make it possible to implement a stable procedure for selecting feedback in control systems for dynamic objects and, thereby, improve the quality of control processes.

For a completely controllable system, the number of nontrivial invariant polynomials of the system matrix is less than the dimension of the control vector; in this case, the problem of constructing a control that leads to
the required spectrum is not solved uniquely. When the system is completely controllable and observable with a one-dimensional input and a multidimensional output, various approaches to determining matrices in controllable, observable linear, multidimensional systems are considered, and these approaches allow arbitrary assignment of the poles of a closed system, i.e. determination of eigenvalues of matrices.

**Development of adaptive-modal control algorithms for dynamic objects**

Assessment of the fulfillment of the conditions of controllability, observability, and non-degeneracy, as well as a qualitative assessment of their degree, are, of course, important stages in the analysis of the properties of objects in the construction of modal control systems with state or input-output controllers. However, it is known [3,4,11,15] that even under the condition of a high degree of controllability and observability of some objects, situations may arise when, as a result of solving the problem of synthesis of a modal control system, solutions with low parametric roughness are obtained.

When managing such objects under conditions of their stability and minimum-phase nature, certain contradictions may arise between the design requirements and the capabilities of the system, which are resolved only due to the appearance of non-minimum-phase links in its structure or the formation of positive feedback on the output coordinate and its derivatives, essentially worsening the robust properties of the ACS [4,8,22].

Consider a linear system with the following difference equation:

\[ A(z^{-1}) y(t) = B(z^{-1}) u(t) + C(z^{-1}) e(t), \]  
where \( A, B, C \) are polynomials for which \( A(0) \) and \( C(0) \) are equal to one, \( B(0) \) is equal to zero, and \( z^{-1} \) is the unit inverse shift operator. Signals correspond to an output, a controlled input, and a zero-mean white noise disturbance.

If we introduce a controller corresponding to the equation [22-24]:

\[ Fu(t) + Gy(t) = 0, \]  
for a closed loop, you can get the equation:

\[ Ty(t) = Fe(t), \]  
which is the pole system for a closed loop is determined by the zeros of the selected polynomial \( T \), provided that \( F \) and \( G \) satisfy the polynomial identity

\[ AF + BG = CT, \]  
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Identity (11) corresponds to a unique solution for \( F \) and \( G \), provided that \( A \) and \( B \) are coprime, and \( n_y \), \( n_z \), and \( n_y \) satisfy the relations: \( n_y = n_y - 1, n_z = n_z - 1 \); \( n_y \leq n_y + n_y - n_z - 1 \). Under these conditions, the solution to equation (11) is obtained by inverting a matrix of order \( n_y + n_y - 1 \). This is one of the disadvantages of this technique, when the calculations must be repeated at each discrete time moment: \( F = T - PB, G = PA \); which satisfies identity (11), for any polynomial \( P \).

The expression (10) is replaced by:

\[ ATy(t) = FCe(t). \]  
In the case when the parameters are unknown, the controller (9), (11) should be synthesized based on the parameter estimates for the selected model structure [2, 12, 23]. The above algorithms turn out to be effective in solving applied problems of identification and synthesis of adaptive control systems for technological objects.

Consider the problem of designing a modal control system for a multidimensional lumped dynamical system. Let a multidimensional system with lumped parameters be described in a vector-matrix form [13, 15, 17, 24]:

\[ \dot{x}(t) = Ax(t) + Bu(t), \quad y(t) = Ce(t), \]  
where \( x(t) \in R^n \) is the state vector of the object; \( u(t) \in R^m \) - control vector; \( y(t) \in R^p \) is the observed output vector; \( A \in R^{n \times n}, B \in R^{n \times m}, C \in R^{p \times n} \) are constant matrices such that pair \( (A, B) \) is controllable, pair \( (A, C) \) is observable, and \( \text{rank}B = m, \text{rank} C = p (2 \leq m, p < n) \).

It is required to obtain the general form of matrices \( K \in R^{p \times r} \) in the control law

\[ u(t) = Ky(t), \]  
which satisfy the condition:

\[ \sigma(A + BK) = \Lambda. \]  
Here \( A + BK \) is a matrix with a simple structure [13, 24], \( \sigma(\cdot) \) is the spectrum of the matrix, and \( \Lambda = \{\lambda_1, \lambda_2, ..., \lambda_n\} \) is a given set of numbers.

Let matrix \( K \in R^{p \times r} \) satisfy condition (12). Then for the matrix \( A + BK \) it is possible to specify \( n \) right \( v_1, v_2, ..., v_n \) and \( n \) left \( w_1, w_2, ..., w_n \) eigenvectors \( (T \) is the transposition symbol), which correspond to the eigenvalues \( \lambda_1, \lambda_2, ..., \lambda_n \) and satisfy the conditions [19, 20]:

\[ v_j \in R^n, w_j \in R^n \text{ at } \lambda_j \in R^1; \]

\[ v_j = \bar{v}_j, w_j = \bar{w}_j \text{ at } \lambda_j = \bar{\lambda}_j; \]

\[ w_i^T v_j = \delta_i(j, 1 \leq i, j \leq n), \]

where \( \delta_i(j) \) is the Kronecker symbol.

Writing equalities:

\[ (A + BK - \lambda I_n) v_i = (A - \lambda I_n, B) \begin{bmatrix} v_i \\ KV_i \end{bmatrix} = 0, \]  
(14)

\[ (A^T + C^T K^T B^T - \lambda I_n) w_i = (A^T - \lambda I_n, C^T) \begin{bmatrix} w_i \\ K^T B^T w_i \end{bmatrix} = 0, \]

where \( I_n \) is the identity \( n \times n \) matrix, \( 0_n \) is the zero \( n \) vector.

We get vectors \((v_i^T, v_i^T C^T K^T)\), \((w_i^T, w_i^T BK)^T\), which are solutions of the equations, respectively:

\[ (A - \lambda I_n, B) v^* = 0_n, \quad (A - \lambda I_n, C^T) x^* = 0_n. \]  
(15)

Let us define matrices \( P, Q \), whose columns form the bases of subspaces of solutions to the first and second
equations from (15), respectively. Since the matrices $A, B, C$ are real and the numbers $\lambda_i \in \Lambda$ are symmetrical about the real axis, it follows that $P_i, Q_i$, can be chosen so that

\[
P_i \in R^{n \times m \times r}, \quad Q_i \in R^{n \times p \times r} \quad \text{at} \quad \lambda_i \in R^1,
\]

\[
P_i = \tilde{P}_i; \quad Q_i = \tilde{Q}_i \quad \text{at} \quad \lambda_i = \bar{\lambda}_j.
\]

(16)

Taking into account the method of obtaining matrices $P_i, Q_i$, for vectors $(v_i', v_i'' C^T)^T$, $(w_i', w_i'' BK)^T$ from (14) we can write:

\[
\begin{bmatrix}
v_i \\
KCV_i
\end{bmatrix} = P_i f_i, \quad \begin{bmatrix}
w_i \\
K' B w_j
\end{bmatrix} = Q_i g_i,
\]

(17)

Here $m$-vectors $f_i$ and $p$-vectors $g_i (i = 1, n)$, according to (13), (16), are such that

\[
f_i \in R^r, \quad g_i \in R^p \quad \text{at} \quad \lambda_i \in R^1;
\]

\[
f_i = \tilde{f}_i; \quad g_i = \tilde{g}_i \quad \text{at} \quad \lambda_i = \bar{\lambda}_j.
\]

Let's represent the matrices $P_i, Q_i$ in the form:

\[
P_i = \begin{bmatrix} S \end{bmatrix}_{m \times n}, \quad Q_i = \begin{bmatrix} T \end{bmatrix}_{n \times p}
\]

(18)

Then, substituting (18) into (17), we have:

\[
v_i = S f_i, \quad w_i'' = g_i T_i^T.
\]

(19)

Since the comoving matrices for $A + BKC$ are related to the eigenvectors $v_i, w_i''$ by formulas

\[
H_i = v_i w_i'' (i = 1, n) \quad [19],
\]

then, taking into account (19), we can write for them that $H_i = S f_i g_i T_i^T$ or

\[
H_i = S_i Z_i T_i^T, \quad (i = 1, n),
\]

(21)

where $Z_i = f_i g_i, Z_i'$.

In the case when the matrices $C$ and $B$ are a matrix of incomplete rank, then the problem under consideration is ill-posed. To give numerical stability to the procedure of pseudo-inversion of matrices $C$ and $B$, it is expedient here to use the concepts of regular methods $[10, 11, 21]$. Let us consider algorithms for stable computation $C^+$ that use certain matrix decompositions $C$ $[15,19,25]$. Whereas if rank$C = p \quad (C \in R^{n \times n}$ with $p \leq n$), then the pseudoinverse of $C$ is a $C^+$ matrix defined by the second Gaussian transformation:

\[
C^+ = C^T (CC^T)^{-1}.
\]

(22)

The validity of expression (22) is since any matrix $C \in R^{n \times n}$ can be represented as a “skeletal” decomposition $[10,19]$:

\[
C = U \cdot V^T,
\]

with matrices $U \in R^{r \times r}$ and $V \in R^{r \times r}$, where

\[r = \text{rank} C \leq \min (p, n).
\]

Let's put it now

\[
C^+ = V^+ \cdot U^+
\]

where, according to (22) and by the property of the pseudoinverse matrix $[19]$, we can come to the following relations:

\[
V^+ = V^T (VV^T)^{-1} \quad \text{and} \quad U^+ = (U^T U)^{-1} U^T.
\]

Then $CC^+C = UVV^T (VV^T)^{-1} (U^T U)^{-1} U^T UV = UV = C$.

If we accept $CC^+C = UVV^T (VV^T)^{-1} (U^T U)^{-1} U^T UV = UV = C$, then we can show that $UC^T = V^+$.

Equation $C^+ = C^+ \Omega$ with $\Omega = U(U^T U)^{-1} (U^T U)^{-1} U^T U$ is also true.

To find the pseudoinverse matrix $B$, one can also use the partition of the matrix into blocks $[11,26,27]$. Let's represent the rectangular matrix $B$ in the form:

\[
B = \begin{bmatrix} J \end{bmatrix} (JP) ,
\]

where $J$ is a nonsingular square matrix $(|J| \neq 0)$. Then the equality $\Theta = \Phi J^+ P$ is true and therefore

\[
B = \begin{bmatrix} J \end{bmatrix} (JP) .
\]

(23)

Since this formula is the result of two successive skeletal expansions:

\[
B = \begin{bmatrix} J \end{bmatrix} (E J^+ P), \quad \left( E J^+ P \right) = J^+ (JP),
\]

\[
B^+ = \left( J^+ P \right). \left( J^+ \right)^{-1} \left( J^+ \Phi \right) \left( J^+ \right)^{-1}.
\]

Then you can come to the expression:

\[
B^+ = \left( J^+ \right)^{-1} (JP) \left( J^+ \right)^{-1} \left( J^+ \Phi \right) \left( J^+ \right)^{-1}.
\]

(23)

Formula (23) gives an explicit expression for the pseudoinverse matrix $B^+$ in terms of blocks $J, P, \Phi$.

The above algorithms make it possible to regularize the considered problem of modal control of multidimensional dynamical objects based on regular methods.

### 3 Objects and Methods

- **Application of the developed synthesis algorithms in the tasks of automation and control of the technological process of ammonia production**

Based on the analysis of the technological process, it was found that the synthesis of ammonia as a control object is characterized by the interaction of controlled parameters $[3,28]$. The process occurring in the column is associated with the release of a significant amount of heat and the slightest changes in the control effects greatly affect the temperature profile of the column. The specifications for reactor temperature control are very stringent: high static accuracy is required, fast temperature equalization, i.e. the speed is high and the dynamic accuracy is significant. In addition, the temperature in the catalyst layers is affected by various disturbing influences, in which the concentration of inert compounds, the ammonia concentration at the reactor inlet, and the ratio of nitrogen and hydrogen are of great importance $[28–30]$.

With this in mind, the following can be considered as the main process variables: control parameters
The topology of these relationships is shown in fig. 1.

![Fig.1. Block diagram of the object](image)

We will describe the dynamics of the main and cross channels of the control object, channels of perturbation using finite-difference equations. After that, in the universal record of the differential equation based on the indexing variable, taking into account the total (measured) outputs, the channel coupling equations are described using the discrete transfer functions $W(z)$ of the plant:

$$y^{(k)}(z) = W^{(k)}(z) \cdot u^{(i)}(z), \quad k = 1, 4, \quad j = 1, 4,$$

where $u^{(i)}(z) \sim \text{control action} \sim y^{(j)}(z) \sim \text{object output};

$$y^{(h)}(z) = \sum_{i=1}^{4} y^{(i)}(z) + \sum_{i=1}^{4} y^{(i)}(z), \quad j = 1, 4,$$

where $u^{(i)}(z)$ is the concentration of ammonia, $f^{(i)}(z)$ is the concentration of inert gases, $f^{(i)}(z)$ is the hydrogen/nitrogen ratio.

Therefore, from the point of view of management, this process is an object with interdependent parameters. The topology of these relationships is shown in fig. 1.

$$u = [u^{[1]}(z), u^{[2]}(z), u^{[3]}(z), u^{[4]}(z)]^T$$

vector of control actions; $f = [f^{[1]}(z), f^{[2]}(z), f^{[3]}(z)]^T$ disturbance vector; $W^{*}$ – triangular matrix of discrete transfer functions of the object in the main and cross channels; $W^{*}_f$ – matrix of discrete transfer functions of the control object through disturbance channels.

Thus, the developed structure of the discrete mathematical model (25) takes into account the one-sided influence of the degree of opening of the dampers in the bypass flows on the temperature in the corresponding and underlying catalyst layers, as well as the influence on the temperature in each layer of disturbing influences: the concentration of ammonia, inert impurities and the ratio of hydrogen and nitrogen. Active experimental methods [31, 32] were used to determine the dynamic properties of the object under study for the main signal transmission channels. Based on the obtained experimental dynamic characteristics of a four-stage ammonia synthesis reactor by the least squares method (quantization cycle $T = 10$ sec.) and differential equations of the first order, a parametric determination of the transfer functions of the main and cross channels of the object was carried out.

The ammonia synthesis reactor is characterized by non-stationarity of dynamic properties, which is associated with a change in catalyst activity and thermophysical properties of the reactor over time. Synthesis of the system requires providing the necessary quality of control based on an adaptive approach. The parameters of the main digital controllers were calculated based on the algorithms developed in the dissertation work. The parameters of discrete transfer functions of cross-connection compensators are calculated.

Based on the analysis of scalar coupling equations, the steps of the current algorithm for identifying the parameters of the models of the main and cross channels of a multi-link control object in a closed control scheme have been developed. Taking into account the developed identification algorithms [6,33-36], taking into account for the non-stationarity of the dynamic characteristics of the reactor, a functional-structural diagram of an adaptive control system for the ammonia production process was proposed (Fig. 2).

The adaptive invariant system [28,36,37] works as follows: the current values of the temperature sensors 2-5 are sent to the block for identifying the parameters of a closed system 8. In this block, the parameters of closed systems are identified. Then the values of the parameters of closed systems are transferred to the block for determining the parameters of the model of the main and cross channels of the control object 9, where the parameters of the control object are determined based on the developed software. The evaluation of the parameters of the object and uncontrolled disturbances is transmitted to the reconfiguration unit of control part 10. In this case, the signals from the sensors for the concentration of ammonia 14, the concentration of inert gases 15, the ratio of the concentration of nitrogen and hydrogen 16, and the flow rate of the circulating gas 13 are fed to the disturbance compensation unit 7, and then to the unit...
reconfiguration of the control part 10. Based on the analysis of the current values of the control actions, the

**Fig.2.** Functional diagram of an adaptive-invariant control system for the ammonia production process

reconfiguration unit of control part 10 determines the linearization interval of the control system for a given mode and transmits this information to the optimization unit of control part 11. Also, the flow rate of the initial nitrogen-hydrogen mixture (NHM) 13 enters the unit temperature optimization 12, where the optimal temperature of the synthesis reaction is determined, which ensures the maximum production of ammonia at a certain NHM flow rate.

Through optimization unit 11 of the control part, the optimal temperature values are fed as control actions to the multichannel adaptive controller 6. In the reconfiguration unit 10, taking into account the nonlinear dependence of the temperature in the first catalyst layer on the degree of damper opening, on based on piecewise linear approximation, one or another piecewise-range model of direct channels for the transmission of influences. Thus, the reconfiguration unit of control part 10, taking into account the information received, calculates the settings of the multi-channel adaptive controller 6, which in turn regulates the bypass flow dampers 17-20.

A simulation block diagram of the ammonia production process control system has been developed. The results of the computer simulation of invariant and adaptive-invariant control systems are presented in fig. 3.

**Fig.3.** Results of computer simulation of invariant (a) and adaptive-invariant (b) systems of control systems
A comparative analysis of transient processes of invariant and adaptive-invariant systems, as well as control quality indicators, allows us to draw the following conclusions: for the first channel, the improvement in quality indicators for the integral square error is 0.5%, for the second - 11.7, for the third and fourth channels - 2.97 and 0.17%. Thus, the use of an adaptive control system makes it possible to stabilize the technological regime of the process under consideration, compensate for the change in the parameters of the object and the influence of uncertain disturbances on the dynamics of the system, and improve the quality indicators of control processes.

Thus, algorithms have been developed for determining the placement of poles in multidimensional systems with proportional-differential feedback on the output, providing the desired distributions on the complex plane of the eigenvalues of the matrix of a closed system. Adaptive algorithms for pole placement of non-minimum-phase stochastic systems in the presence of white noise at the output are developed, which make it possible to exclude the operation of matrix inversion, which requires significant computational costs. Algorithms for selecting feedback in control systems of dynamic objects have been developed, which allow for stable identification of the coefficients of the object equations and the observed values of the object used in the control device. Algorithms for adaptive control based on the modal method for dynamic objects with delay under conditions of a priori uncertainty and non-stationarity of the process parameters are developed, which provide exponential dissipativity of the control process. Based on the developed regular algorithms, an adaptive control system for the ammonia synthesis process is proposed. The proposed adaptive control system makes it possible to stabilize the technological regimes of the process and increase the efficiency of its operation.

4 Conclusions

Based on the methods of system analysis, identification, the theory of automatic control, evaluation, adaptive-modal control, processing of experimental results and methods for solving ill-posed problems, constructive algorithms for the synthesis of control systems for dynamic objects based on the modal method were developed in the article and, as a result, the following scientific results were obtained:

Algorithms for determining the placement of poles in multidimensional systems with proportional-differential output feedback are developed, which provide the desired distributions on the complex plane of the eigenvalues of the matrix of a closed system.

An efficient algorithm for solving the problem of placing poles of multidimensional invariant systems with feedback has been developed. This algorithm is efficient for desired eigenvalues that are real, complex conjugate, and repeating poles.

We propose adaptive algorithms for pole placement of non-minimum-phase stochastic systems in the presence of white noise at the output, which make it possible to exclude the operation of matrix inversion, which requires significant computational costs.

Algorithms for adaptive control based on the modal method for dynamic objects with delay under conditions of a priori uncertainty and non-stationarity of the process parameters are developed, which provide exponential dissipativity of the control process. Based on the developed regular algorithms, an adaptive control system for the ammonia synthesis process is proposed. The proposed adaptive control system based on modal methods makes it possible to stabilize the technological regimes of the process and increase the efficiency of its operation.

References


