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AN UPDATING METHOD FOR THE DYNAMIC MIMO MODEL OF A CONTROLLED TECHNOLOGICAL OBJECT

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Abstract. This paper considers the degradation of MIMO models of controlled industrial processes. We propose a method for solving a nonlinear programming problem with an objective function formed by the least squares method according to technological object data. The method involves dynamic process modeling algorithms based on the imposition of the step response of the process. The advantage of this method is the possibility of using passive experiment data to construct an appropriate multi-loop model of a technological object. The method is applied to update the multiparameter controller model for the Advanced Process Control system of butyraldehydes oxo synthesis. For real controlled technological objects, this method allows improving the accuracy of process modeling and the performance of automatic control, reducing the human factor, and increasing the overall economic efficiency of the production process.

Keywords: MIMO system, transfer function, Model Predictive Control, Advanced Process Control.

INTRODUCTION

For reaching maximum production efficiency, many high-tech solutions are being actively implemented at modern enterprises to optimize processes at all production stages and provide the high adaptability of production units to the current economic and technological conditions [1–4]. One of such solutions is Advanced Process Control (APC) systems [5].

In the overwhelming majority of cases, the concept of advanced control of continuous industrial processes involves dynamic models predicting the behavior of controlled process parameters. Predictive control algorithms are implemented based on the calculations to stabilize an industrial process, compensating for the effect of disturbances on the controlled parameters, and bring the technological object to an optimal mode by an economic criterion under given technological constraints [6–8].

1. DEGRADATION OF DYNAMIC MODELS: PROBLEM STATEMENT

A key requirement for MIMO control systems is the accuracy of the structural and parametric identification of control loops [9, 10]. According to the classical approach, the dynamics are described by a system of linear differential equations written as a matrix transfer function of dimensions $p \times q$, where p is the number of controlled variables and q is the total number of manipulated variables and observed disturbance variables. The model inputs are the manipulated variables of the process and the detected disturbance variables; at its output, the model predicts the behavior of the controlled variables of the process. In general, such a model has the form:

$$W(s) = \frac{A(s)}{B(s)} e^{-\tau s} = \\ = \frac{a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0}{b_m s^m + b_{m-1} s^{m-1} + \ldots + b_1 s + b_0} e^{-\tau s}, \quad (1)$$

where s denotes the Laplace operator; $A(s)$ and $B(s)$ are the polynomial representations of the numerator and denominator, respectively; n and m are the degrees of the polynomials $A(s)$ and $B(s)$, respectively. The physical implementability condition is given by $n \le m$.

This approach to describing the controlled object is accompanied by the degradation of the MIMO model (1) due to nonlinear physical and chemical processes

[11]. Therefore, control models for continuous industrial processes need to be periodically adjusted to the current technological mode [12]. A typical solution is to conduct an active experiment (step-by-step testing) to read the response characteristics of the process and update the MIMO model of the controlled object. A drawback of this approach is applying strong controls to a continuously operating object, which may destabilize the technological mode and bring the controlled variables of the process and key quality indicators of the products beyond the permissible limits.

2. DESCRIPTION OF THE UPDATING METHOD

Considering the range of problems mentioned, we develop an updating method for the dynamic MIMO model based on passive experiment data analysis. This method involves a nonlinear programming problem with an objective function formed by the least squares method according to technological object data:

$$\min_{k,a,b,\tau} \sum_{i=1}^{N} \left(y_i^e - y_i^{ap}(k,\, a,\, b,\, \tau) \right)^2 \to \to k^0,\, a^0,\, b^0,\, \tau^0, \tag{2}$$

where N denotes the size of the initial data sample; y_i^e are the real values of controlled variables; $y_i^{ap}(k, a, b, \tau)$ are the values predicted by the model; k is the gain matrix of dimensions $1 \times q$; a is the coefficient matrix of the polynomial $A(s)$ of dimensions $n \times q$; b is the gain matrix of the polynomial $B(s)$ of dimensions $m \times q$; τ is the time delay matrix of dimensions $1 \times q$; finally, k^0, a^0, b^0, and τ^0 are the estimates of the transfer function parameters.

The predicted values are calculated using the imposition of the step response of the process:

$$y_i^{ap} = \sum_{j=1}^{i-1} \Delta x_j^{\mathrm{T}} h\left(\Delta T \left[i - j \right] \right) + y_1^e,\ i = \overline{2, N},$$

where $\Delta x = x_j - x_{j-1}$ is the step excitation matrix of the input signals of dimensions $q \times 1$; $h(t)$ is the step responses of the control loops; ΔT is the sampling interval.

According to the residue theorem, the step response of the loop has the form

$$h(t) = \sum_{r=1}^{n} \mathrm{Res}_{s=s_r} \left[W(s_r) e^{s_r t} \right],$$

where s_r is a pole of the function $W(s)$.

In the general case of n simple nonzero poles (the transfer function has one zero pole and n simple poles), the step response can be calculated as

$$h(t) = \frac{B(0)}{A(0)} + \sum_{r=1}^{n} \frac{B(s_r) e^{s_r t}}{s_r A'(s_r)}, \tag{3}$$

where $A'(s_r)$ denotes the derivative of the characteristic polynomial $A(s)$ calculated at the pole r [13].

For advanced process control, the dynamics of the control loops can be described with sufficient precision by a second-order differential equation with the transfer function [14]

$$W(s) = k \frac{a_1 s + 1}{b_2 s^2 + b_1 s + 1} e^{-\tau s}. \tag{4}$$

For the dynamics (4), the step response formula (3) reduces to

$$h(t) = k \left(1 + \frac{(c_1 - a_1) e^{-\frac{t-\tau}{c1}} - (c_2 - a_1) e^{-\frac{t-\tau}{c_2}}}{c_2 - c_1} \right),$$

where $c_1 = -s_1^{-1}$, $c_2 = -s_2^{-1}$, and $s_{1,2}$ are the poles of the transfer function (4).

After the transformations of the objective function, the nonlinear programming problem (2) is written as

$$\min_{k,a_1,c_1,c_2,\tau} \sum_{i=2}^{N} \left(y_i^e - y_1^e - \sum_{j=1}^{i-1} \Delta x_j^{\mathrm{T}} h\left(\Delta T \left[i - j \right] \right) \right)^2 \to \to k^0,\, a_1^0,\, c_1^0,\, c_2^0,\, \tau^0 \tag{5}$$

where

$$h_r\left(\Delta T \left[i - j \right] \right) = = k_r \left(1 + \frac{(c_{1r} - a_{1r}) e^{-\frac{\Delta T (i-j) - \tau_r}{c_{1r}}} - (c_{2r} - a_{1r}) e^{-\frac{\Delta T (i-j) - \tau_r}{c_{2r}}}}{c_{2r} - c_{1r}} \right),$$

$$r = \overline{1, q}.$$

When necessary, we can easily pass from the poles c_1 and c_2 to the desired coefficients of the polynomial $B(s)$:

$$b_{1r} = c_{1r} + c_{2r},\ b_{2r} = c_{1r} c_{2r},\ r = \overline{1, q}.$$

The starting point for object identification can be the current parametric configuration of the MIMO model and a given set of parameters based on the appropriation of the passive experiment data.

Due to the amount of required calculations and the parametric dimension of the objective function, problem (5) should be solved using methods with a high convergence rate. In particular, the class of quasi-Newtonian methods with the Hessian calculated by *the*

Broyden–Fletcher–Goldfarb–Shanno algorithm [15] can be employed.

In practice, the method is implemented by adjusting the object model in automatic mode according to a given quantitative criterion or in manual mode following the request of the operating personnel.

3. APPLICATION OF THE UPDATING METHOD

The updating method for the MIMO model of controlled objects was tested on a real technological object: an industrial installation for butyraldehydes oxo synthesis to produce butyl alcohols. The installation has a continuous scheme: its key part is a hydroformylation unit to produce normalbutyraldehydes and isobutyraldehydes from propylene and synthesis gas in the presence of cobalt hydrocarbonyl in series reactors R-3 and R-4 with a catalyst from Cobalt 2- ethylhexanate and synthesis gas prepared in reactor R-1. The catalytic mixture is purified from fuel gases in high- and low-pressure separators (S-1 and S-2, respectively) and enters the oxidative decobaltization unit for the further processing of the key catalyzate components.

Butyl alcohol production has an APC system. A fragment of this system—the hydroformylation unit with the process parameters involved—is shown in the general process flow diagram of the installation (Fig. 1 and Table 1).

Table 1

Variables of APC system controller

Tag	Description
1. Controlled variables	
cv1	Propylene conversion
cv2	Propylene losses in blow-off
2. Manipulated variables	
mv1	Consumption of propane-propylene fraction
mv2	Temperature in reactor R-3
mv3	Temperature in reactor R-4
mv4	Gas pressure in high-pressure separator S-1
mv5	Consumption of catalytic mixture
mv6	Gas pressure in low-pressure separator S-2
3. Disturbance variables	
dv1	Carbon monoxide (CO) content in synthesis gas
dv2	Hydrogen concentration in synthesis gas

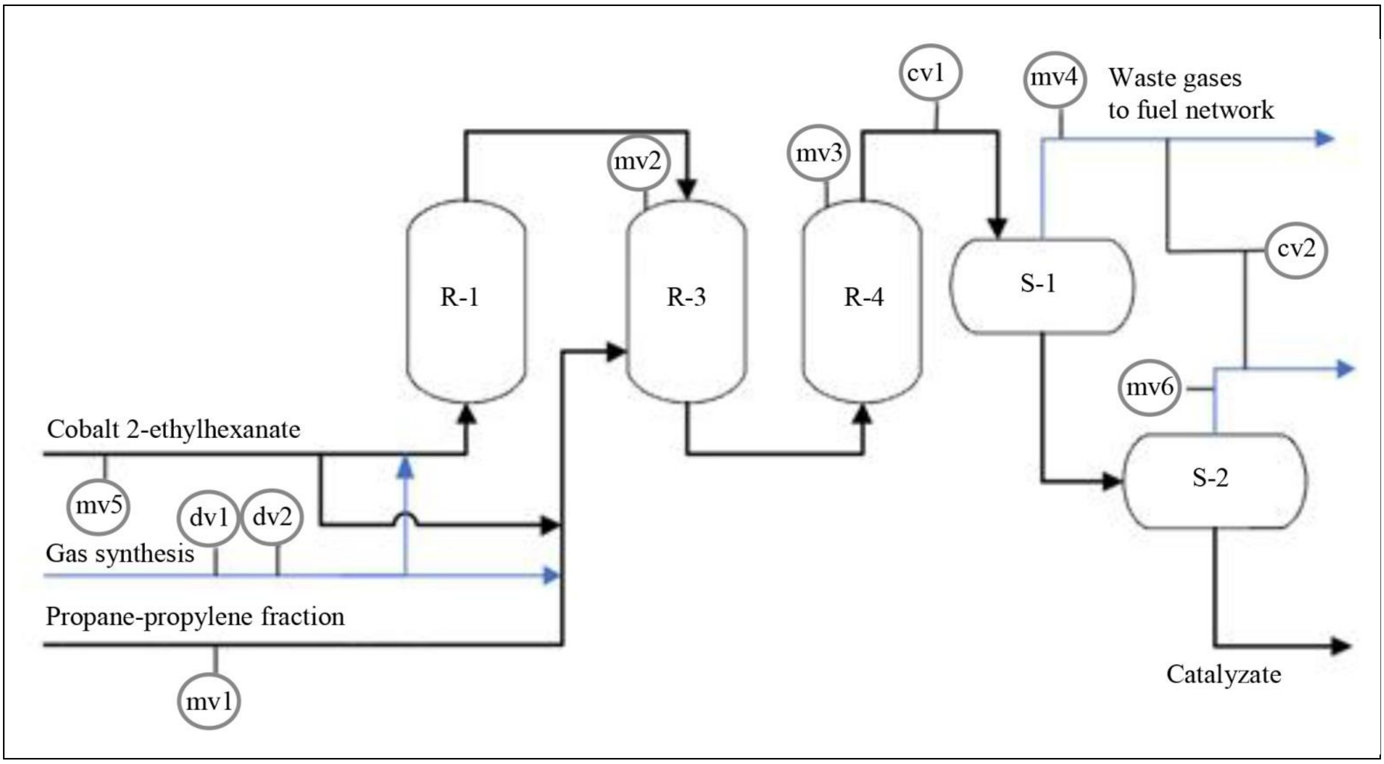

Fig. 1. Hydroformylation unit.

For this part of the APC controller of the hydroformylation unit, the developed method was applied to identify the MIMO model and update its parametric and structural configuration according to the current technological mode. Table 2 shows the results of updating the dynamic controller model.

The identification procedure was assessed by testing the model on a sample of historical industrial process data. Based on the results of model tests, the graphs of propylene conversion (Fig. 2) and propylene losses in blow-off (Fig. 3) predicted by the original and updated models on the same set of initial data were obtained.

Table 2

Updating the dynamic model of the hydroformylation unit

		Original model		Updated model	
		Output signal			
		cv1	cv2	cv1	cv2
Input signal	mv1	$0.0353\frac{1}{20s+1}$	$8.82\frac{1}{20s+1}$	$0.0353\frac{1}{20s+1}$	$12.36\frac{1}{18.93s+1}$
	mv2	$0.0678\frac{1}{15s+1}$	$-13\frac{0.51s+1}{3.89s^2+2.36s+1}$	$0.0348\frac{1}{18.82s+1}$	$-4.5\frac{1.41s+1}{3.76s^2+1.54s+1}$
	mv3	$0.0025\frac{1}{15s+1}e^{-4s}$	$-15.3\frac{1}{130s^2+22.8s+1}$	$0.0016\frac{1}{11.34s+1}e^{-6s}$	$-7.01\frac{0.21s+1}{130s^2+23s+1}$
	mv4	$0.007\frac{1}{5s+1}e^{-3s}$	–	$0.009\frac{1}{5s+1}e^{-3s}$	–
	mv5	$0.021\frac{1}{6.25s^2+5s+1}$	$-68.2\frac{1}{10.1s+1}e^{-6s}$	$0.021\frac{1}{6.25s^2+5s+1}$	$-68.2\frac{1}{10.1s+1}e^{-6s}$
	mv6	–	$-86.1\frac{1}{15s+1}$	–	$-83\frac{1}{15s+1}$
	dv1	$0.0021\frac{1}{12s+1}e^{-2s}$	$19.4\frac{1}{22.4s+1}e^{-24s}$	$0.0021\frac{1}{12s+1}e^{-2s}$	$19.19\frac{1}{22.4s+1}e^{-23s}$
	dv2	$0.01\frac{2.57s+1}{9.22s^2+6.72s+1}$	$0.659\frac{1}{12s+1}e^{-2s}$	$0.01\frac{2.57s+1}{9.22s^2+6.72s+1}$	$1.132\frac{1}{12s+1}e^{-2s}$

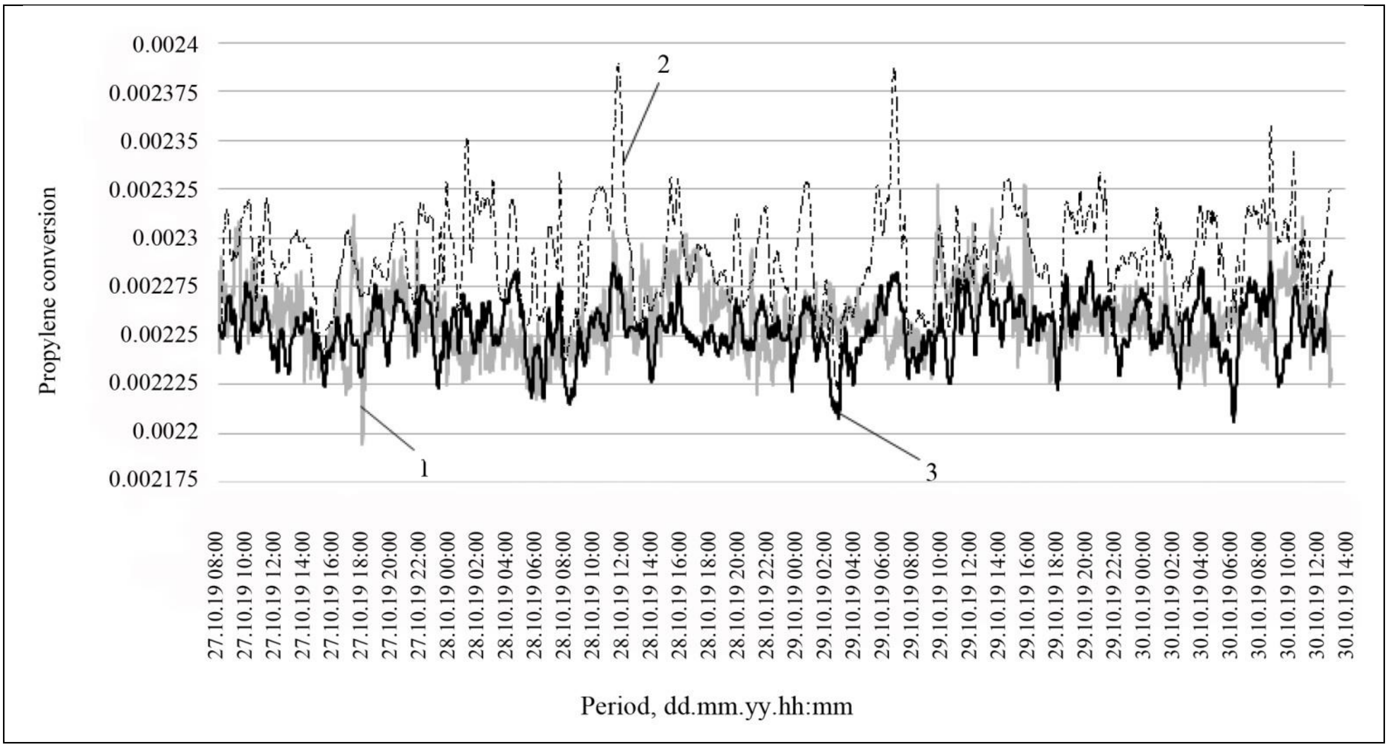

Fig. 2. Propylene conversion: (*1*) real values, (*2*) original model, and (*3*) updated model.

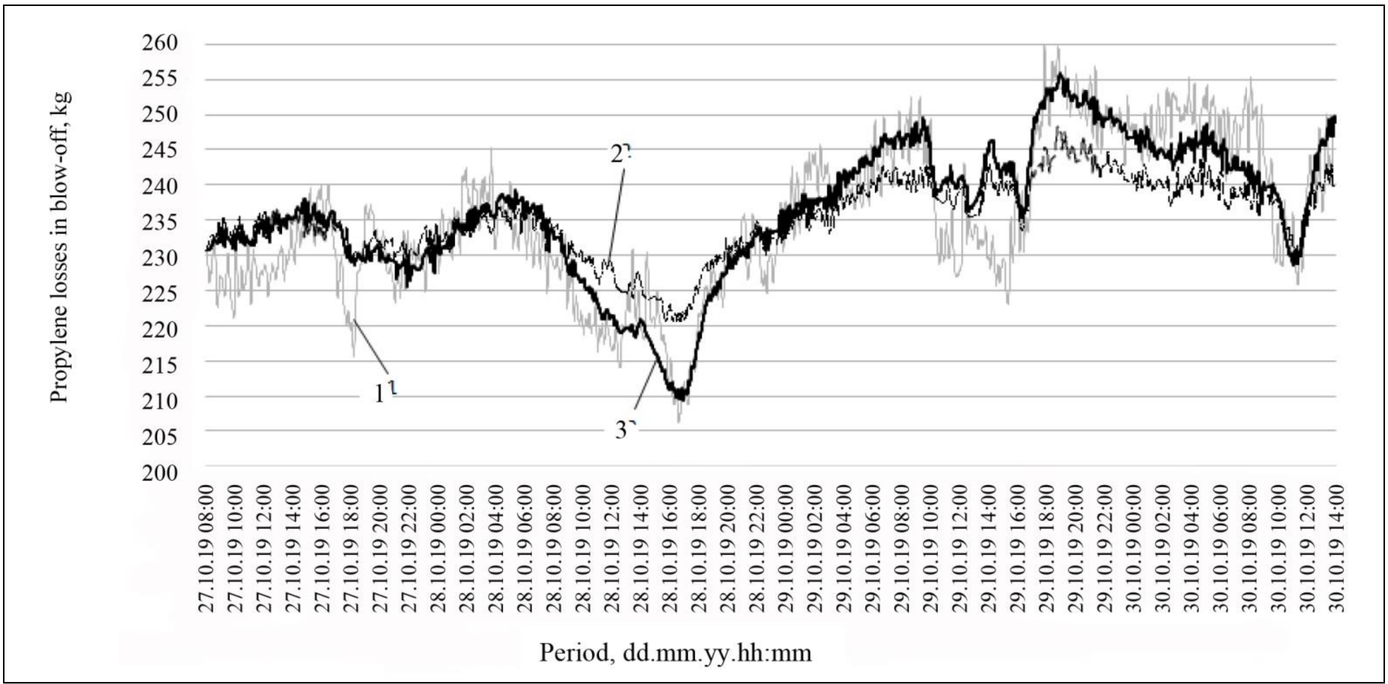

Fig. 3. Propylene losses in blow-off: (*1*) real values, (*2*) original model, and (*3*) updated model.

As the result of updating, the standard deviation of the predicted values from the real ones decreased from 4.159×10^{-5} to 2.045×10^{-5} (propylene conversion) and from 6.483 kg to 5.112 kg (propylene losses in blow-off).

CONCLUSIONS

This paper has presented a new method for updating the dynamic MIMO model of a controlled technological object. The method involves a nonlinear programming problem with an objective function formed using the least squares method. A distinctive feature of the developed method is the ability to model the transient processes of the control loops based on the previous structural and parametric identification. An advantage of the method is that there is no need to conduct an active experiment at the industrial installation: historical data of the technological process are used to update the model.

The developed method has been applied to the MIMO model of the APC system of the hydroformylation unit within an industrial installation for butyraldehydes oxo synthesis to produce butyl alcohols. As the result of updating, the standard deviation of the predicted values from the real ones has been reduced by factors of 2.033 (propylene conversion) and 1.268 (propylene losses in blow-off).

The new method improves the modeling accuracy of ongoing physical and chemical processes. In advanced process control, it enhances the performance of automatic control of an industrial process, stabilizing its key controlled variables and decreasing the dispersion of laboratory readings. Consequently, the overall economic efficiency of the production process is increased, and the human factor in an industrial process is reduced.

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