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МОДЕЛЮВАННЯ ОПТИМАЛЬНИХ РЕГУЛЯТОРІВ ДЛЯ ТЕПЛОВОГО РЕЖИМУ НАХИЛЕНОЇ ДИФУЗІЙНОЇ УСТАНОВКИ ЦУКРОВОГО ЗАВОДУ

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SIMULATION OF OPTIMAL CONTROLS FOR THERMAL MODE OF SUGAR FACTORY INCLINED DIFFUSION APPARATUS

МОДЕЛИРОВАНИЕ ОТИМАЛЬНЫХ РЕГУЛЯТОРОВ ДЛЯ ТЕПЛОВОГО РЕЖИМА НАКЛОНЕННОЙ ДИФУЗИОННОЙ УСТАНОВКИ САХАРНОГО ЗАВОДА

Abstract

The work compares two regulators for optimal temperature regime inclined diffusion apparatus of sugar factory. First synthesized by standard algorithms ACOr and second with same algorithm, but with the introduction of an integrated component on error signal. Based on the heat balance of the mathematical model of control object, which consists of eight linear differential equations, the model coefficients are calculated and presented it to the space of state variables. Based on the simulation show that the control system, which is synthesized by ACOr insignificant static error that allowed for technological regulations diffusion process. The use of optimal control algorithm with integral component of the error signal by significantly delaying transients in the system although it eliminates static error, because the latter algorithm impractical to use.

Key Words

Mathematical model of the control object, heat exchange, mass transfer, diffusion apparatus, algorithm of optimal control.

Анотація

В роботі проводиться порівняння двох оптимальних регуляторів для температурного режиму нахиленої дифузійної установки цукрового заводу. Перший синтезований за стандартним алгоритмом АКОР, а другий за вказаним алгоритмом, але з введенням інтегральної складової за сигналом розузгодження. На основі теплового балансу розроблено математичну модель об'єкта керування, що складається з восьми лінійних диференціальних рівнянь, розраховані коефіцієнти моделі та приведено її до простору змінних стану. На основі моделювання показано, що система з регулятором, який синтезований за АКОР має несуттєву статичну похибку, що допустима за технологічним регламентом процесу дифузій. А застосування алгоритму оптимального керування з інтегральною складовою за сигналом розузгодження значно затягує перехідні процеси в системі хоча і ліквідує статичну похибку, тому останній алгоритм недоцільний в застосуванні.

Ключові слова

Математична модель об'єкта управління, теплообмін, масообмін, дифузійний апарат, алгоритм оптимального управління.

Аннотация

В работе проводится сравнение двух оптимальных регуляторов для температурного режима наклоненной диффузионной установки сахарного завода. Первый был синтезирован по стандартному алгоритму АКОР, а второй при помощи указанного алгоритма, но с введением интегральной составляющей по сигналу рассхождения. На основе теплового баланса разработана математическая модель объекта управления, состоящая из восьми линейных дифференциальных уровнений, рассчитаны коэффициенты модели. На основе моделирования показано, что система с регулятором, который синтезированний за АКОР имеет несущественную статическую погрешность, что допустимая по тех-нологических регламентам процесса диффузии. А применение алгоритма оп-минимального управления с интегральной составляющей по сигналу рассогласования значительно затягивает переходные процессы в системе хотя и ликвидирует статическую погрешность, поэтому последний алгоритм нецелесообразен в применении.

Ключевые слова

Математическая модель объекта управления, теплообмен, массообмен, дифузионный аппарат, алгоритм оптимального управления.

Abbreviations

ACO- ant colony optimization

ACOr- ant colony optimization for continuous domains

Problem formulation

In the process of complex with continuous type function technological objects, which are characterized by many interconnected regulated coordinates. Often several controlled origin, whose number n ≥ 4 have the same physical nature and contours of regulation are based on the same structure. This applies, for example, diffusion plants gentle slope-type sugar mills, which are governed by n ≥ 4 temperatures in different zones.

Thus, food enterprises can be identified class of objects [1], which are characterized by the following properties:

- Have the same coordinate state n≥4 a physical nature;
- Have significant internal relationships between variables;
- Similar in structure to describe mathematical models;
- Governed by a similar scheme.

In traditional systems automation to adjust each of the coordinates of the object class uses a separate automatic regulator, leading to undesirable influences one path to the other and, consequently, deterioration in the quality of transients and increase energy.

Highlight unsolved parts of the general problem

The use of autonomous systems leads to complexity of the structure of the system by including joints and does not provide a significant improvement of quality of transients. Therefore, to build a system of such objects must use an approach in which the optimality conditions will be carried out on the quality of the transition process, reducing the cost of energy and the autonomy of individual control channels. Among a variety of algorithms for optimal control of industrial objects [2] are algorithms for multidimensional systems with control criterion corresponds to the aim of the study. This algorithm analytic construction of optimal regulators (LQR), for which at present there are many additions and extensions.

The purpose of the research problem

Compare discrete system of automatic regulation of the optimal control for the diffusion apparatus of the sugar factory, a synthesis algorithm ACOr with the introduction of an integrated component on error signal and without during task change.

Comparison of optimal controls carried out by simulation using application package Matlab, which are ready mentioned algorithms that significantly reduce the time writing and debugging programs.

Materials and Method

The mathematical model of control object. The object is inclined diffusion apparatus for sugar production, which has four zones with one steam chamber (Fig. 1) [1].

A mathematical model is developed under the following assumptions:

- Object (diffusion part of heat exchange apparatus) consider lumped parameters;
- Diffusion apparatus has an ideal thermal insulation for neglecting losses to the environment;
- The couple of steam chambers is in the state of saturation, and the enthalpy of the heating steam and the enthalpy of the steam chamber adopt the same as the consumption of steam and condensate;
- Takes in a constant specific heat capacity beet chips and juice, heat transfer coefficient and density of juice and beet chip mixture;
- Thermal diffusion facility design capacity is not considered.

Derive the equation for the second heat exchange zone beet chips and juice mixture, which make up the heat balance equation

$$G_c^{12}C_c^{12}\theta_1 + G_{\partial c}^{32}C_{\partial c}^{32}\theta_3 + kF(\theta_{n2} - \theta_2) = G_c^{23}C_c^{23}\theta_2 + G_{\partial c}^{21}C_{\partial c}^{21}\theta_2, \quad (1)$$

where G_c^{ij}, $G_{дc}^{ij}$, C_c^{ij}, $C_{дc}^{ij}$ – consumption and heat capacity beet chips and juice from the i-th to the j-th zone under; θ_i, θ_{nj} – temperature juice and chips mixture of steam in a steam chamber in the i-th zone under; k, F – heat transfer coefficient and area heating steam chamber.

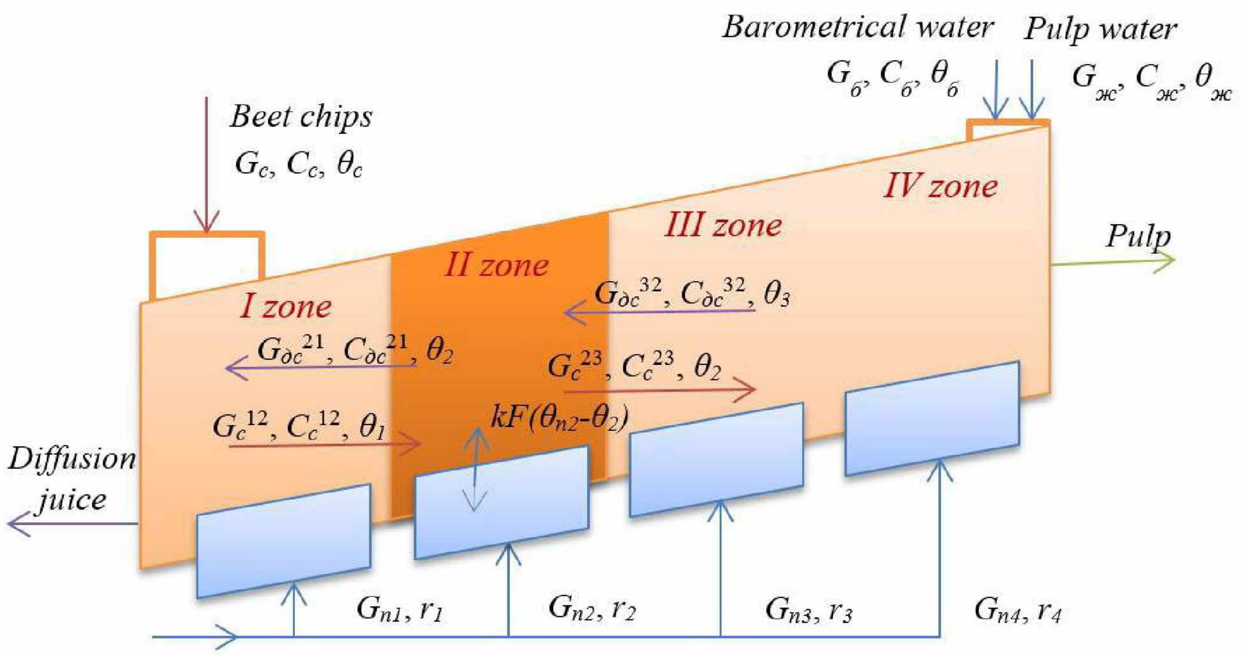

Fig.1. Simplified flowsheet gentle slope diffusion apparatus

When imbalance will occur a change in heat capacity at a speed dependent on the imbalance

$$MH_2 L\rho c_2 \frac{d\theta_2}{d\tau} = \Delta(G_c^{12}C_c^{12}\theta_1 + G_{дс}^{32}C_{дс}^{32}\theta_3 + kF(\theta_{п2}-\theta_2) - G_c^{23}C_c^{23}\theta_2 - G_{дс}^{21}C_{дс}^{21}\theta_2), \quad (2)$$

where M, H_i, L, ρ, c_i – width, height and length of the device, density and heat capacity chips juice mixture, respectively.

In deviations of variables based on linearization equation becomes:

$$\frac{d\theta_2}{d\tau} = \frac{1}{MH_2 L\rho c_2}(G_{c_0}^{12}C_c^{12}\Delta\theta_1 + C_c^{12}\theta_{1_0}\Delta G_c^{12} + G_{дс_0}^{32}C_{дс}^{32}\Delta\theta_3 + C_{дс}^{32}\theta_{3_0}\Delta G_{дс}^{32} +$$

$$+ kF\Delta\theta_{п2} - kF\Delta\theta_2) - G_{c_0}^{23}C_c^{23}\Delta\theta_2 - C_c^{23}\theta_{2_0}\Delta G_c^{23} - G_{дс_0}^{21}C_{дс}^{21}\Delta\theta_2 - C_{дс}^{21}\theta_{2_0}\Delta G_{дс}^{21}, \quad (3)$$

For other areas beet chips and juice mixture equations are derived similarly.

Derive the equation of heat transfer for steam capacity. Putting the heat balance equation:

$$G_{п1}r_1 = kF(\theta_{п1} - \theta_1), \quad (4)$$

where $G_{пi}$, r_i – steam flow in the steam chamber and heat of vaporization in the i-th zone diffusion apparatus. When imbalance will occur a change in heat capacity at a speed dependent on the imbalance:

$$Vc_{п1}\frac{d\theta_{п1}}{d\tau} = \Delta(G_{п1}r_1 - kF\theta_{п1} + kF\theta_1), \quad (5)$$

where V, $c_{пi}$ – volume of the steam chamber and heat of steam in the i-th zone, respectively.

Turn to deviations:

$$\frac{d\theta_{п1}}{d\tau} = \frac{1}{Vc_{п1}}(r_1\Delta G_{п1} - kF\Delta\theta_{п1} + kF\Delta\theta_1). \quad (6)$$

The heat capacity of steam depends on the internal energy of steam $u_п$ and vapor density ρ'':

$$c_{п1} = u_п a + \rho'' b,$$
$$\rho'' = \overline{\rho}'' + a\theta_п; \quad (7)$$
$$u_п = \overline{u}_п + b\theta_п;$$

where $\overline{\rho}'', \overline{u}_п, a, b$ – determined experimentally.

In [2, 3], the concentration of sugar in the juice and chips on the current length of the diffusion apparatus l is described exponential dependence. According consumption and heat capacity of chips and juice for long diffusion apparatus can be described :

$$G_c = 31{,}25e^{-0.00759l}, \quad [kg/sec],$$
$$G_{дс} = 37{,}5e^{-0.00623l}, \quad [kg/sec], \quad (8)$$
$$C_c = 3{,}40e^{0.00759l}, \quad [kJ/kg\ ^0C],$$
$$G_{дс} = 3{,}61e^{0.00623l}, \quad [kJ/kg\ ^0C].$$

The result is a mathematical model of heat transfer diffusion apparatus:

$$
\begin{cases}
\dfrac{d\Delta\theta_1}{d\tau} = \dfrac{1}{MLH_1\rho c_1}\left(G_{c_0}^{01}C_c^{01}\Delta\theta_c + (C_c^{01}\theta_{0_0} - C_c^{12}\theta_{1_0})\Delta G_c + G_{\partial c_0}^{21}C_{\partial c}^{21}\Delta\theta_2 + \right. \\
\left. + (C_{\partial c}^{21}\theta_{2_0} - C_{\partial c}^{10}\theta_{1_0})\Delta G_{\partial c} + kF\Delta\theta_{n1} - (kF + G_{c_0}^{12}C_c^{12} + G_{\partial c_0}^{10}C_{\partial c}^{10})\Delta\theta_1\right); \\
\dfrac{d\Delta\theta_2}{d\tau} = \dfrac{1}{MLH_2\rho c_2}\left(G_{c_0}^{12}C_c^{12}\Delta\theta_1 + (C_c^{12}\theta_{1_0} - C_c^{23}\theta_{2_0})\Delta G_c + G_{\partial c_0}^{32}C_{\partial c}^{32}\Delta\theta_3 + \right. \\
\left. + (C_{\partial c}^{32}\theta_{3_0} - C_{\partial c}^{21}\theta_{2_0})\Delta G_{\partial c} + kF\Delta\theta_{n2} - (kF + G_{c_0}^{23}C_c^{23} + G_{\partial c_0}^{21}C_{\partial c}^{21})\Delta\theta_2\right); \\
\dfrac{d\Delta\theta_3}{d\tau} = \dfrac{1}{MLH_3\rho c_3}\left(G_{c_0}^{23}C_c^{23}\Delta\theta_2 + (C_c^{23}\theta_{2_0} - C_c^{34}\theta_{3_0})\Delta G_c + G_{\partial c_0}^{43}C_{\partial c}^{43}\Delta\theta_4 + \right. \\
\left. + (C_{\partial c}^{43}\theta_{4_0} - C_{\partial c}^{32}\theta_{3_0})\Delta G_{\partial c} + kF\Delta\theta_{n3} - (kF + G_{c_0}^{34}C_c^{34} + G_{\partial c_0}^{32}C_{\partial c}^{32})\Delta\theta_3\right); \\
\dfrac{d\Delta\theta_4}{d\tau} = \dfrac{1}{MLH_4\rho c_4}\left(G_{c_0}^{34}C_c^{34}\Delta\theta_3 + (C_c^{34}\theta_{3_0} - C_c^{4в}\theta_{4_0})\Delta G_c + G_{б_0}C_б\Delta\theta_б + \right. \\
+ G_{ж c_0}C_{ж c}\Delta\theta_{ж c} - C_{\partial c}^{43}\theta_{4_0}\Delta G_{\partial c} + C_б\theta_{б_0}\Delta G_б + C_{ж c}\theta_{ж c_0}\Delta G_{ж c} + kF\Delta\theta_{n4} - \\
\left. - (kF + G_{c_0}^{4в}C_c^{4в} + G_{\partial c_0}^{43}C_{\partial c}^{43})\Delta\theta_4\right); \\
\dfrac{d\Delta\theta_{n1}}{d\tau} = \dfrac{1}{Vc_{n1}}(r_1\Delta G_{n1} - kF\Delta\theta_{n1} + kF\Delta\theta_1); \\
\dfrac{d\Delta\theta_{n2}}{d\tau} = \dfrac{1}{Vc_{n2}}(r_2\Delta G_{n2} - kF\Delta\theta_{n2} + kF\Delta\theta_2); \\
\dfrac{d\Delta\theta_{n3}}{d\tau} = \dfrac{1}{Vc_{n3}}(r_3\Delta G_{n3} - kF\Delta\theta_{n3} + kF\Delta\theta_3); \\
\dfrac{d\Delta\theta_{n4}}{d\tau} = \dfrac{1}{Vc_{n4}}(r_4\Delta G_{n4} - kF\Delta\theta_{n4} + kF\Delta\theta_4);
\end{cases}
\quad (9)
$$

where $\Delta\theta_c, \Delta\theta_б, \Delta\theta_{ж c}$ – deviation chips temperature at the entrance of the diffusion apparatus, barometric and pulp water respectively; $\Delta G_б, \Delta G_{ж c}$, $\Delta C_б, \Delta C_{ж c}$ – deviation expenses and heat capacity of barometric and pulp water respectively.

As can be seen from the model object is multiply connected, change the temperature of a beet chips and juice mixture θ_i leads to changes in temperature and vapor beet chips and juice mixture both direct and reverse. If the trace variables $\Delta G_{\partial c}, \Delta G_c$, then rejection leads to changes $\Delta\theta_i$ in direct (direct impact) and return path, and through $\Delta\theta_i$ – to change $\Delta\theta_{ni}$, which in turn will also affect $\Delta\theta_i$. Change of $\Delta G_{ж c}, \Delta G_б, \theta_{ж c}, \theta_б$ leads to changes $\Delta\theta_4$, acting on a return path to change $\Delta\theta_i$ та $\Delta\theta_{ni}$.

For stationary mode operation of the sugar plant capacity of 3000 tons / day, calculated values of the coefficients of the mathematical model of the object for the typical modes of operation based on the design features of the facility. Mathematical model of heat exchange diffusion system brought to the form (machine time τ=100t, where τ, sec):

$$\begin{cases} 1.157\dfrac{d\Delta\theta_1}{dt} + \Delta\theta_1 = 0.43\Delta\theta_c + 0.54\Delta\theta_2 + 0.03\Delta\theta_{n1} - 0.27\Delta G_c + 0.15\Delta G_{\partial c}; \\ 1.169\dfrac{d\Delta\theta_2}{dt} + \Delta\theta_2 = 0.43\Delta\theta_1 + 0.54\Delta\theta_3 + 0.03\Delta\theta_{n2} - 0.14\Delta G_c + 0.04\Delta G_{\partial c}; \\ 1.181\dfrac{d\Delta\theta_3}{dt} + \Delta\theta_3 = 0.43\Delta\theta_2 + 0.54\Delta\theta_4 + 0.03\Delta\theta_{n3} - 0.04\Delta G_c + 0.03\Delta G_{\partial c}; \\ 1.193\dfrac{d\Delta\theta_4}{dt} + \Delta\theta_4 = 0.43\Delta\theta_3 + 0.33\Delta\theta_{\delta} + 0.03\Delta\theta_{n4} + 0.21\Delta\theta_{ж} + 0.92\Delta G_{\delta} + \\ \qquad + 0.92\Delta G_{ж} - 0.87\Delta G_{\partial c} + 0.09\Delta G_c; \\ 0.0887\dfrac{d\Delta\theta_{n1}}{dt} + \Delta\theta_{n1} = \Delta\theta_1 + 279.91\Delta G_{n1}; \\ 0.0393\dfrac{d\Delta\theta_{n2}}{dt} + \Delta\theta_{n2} = \Delta\theta_2 + 288.9\Delta G_{n2}; \\ 0.0489\dfrac{d\Delta\theta_{n3}}{dt} + \Delta\theta_{n3} = \Delta\theta_3 + 286.5\Delta G_{n3}; \\ 0.0715\dfrac{d\Delta\theta_{n4}}{dt} + \Delta\theta_{n4} = \Delta\theta_4 + 282.3\Delta G_{n4}, \end{cases} \tag{10}$$

Transformed model to the space of state variables:

$$\mathbf{x}(t) = [\Delta\theta_1, \Delta\theta_2, \Delta\theta_3, \Delta\theta_4, \Delta\theta_{n1}, \Delta\theta_{n2}, \Delta\theta_{n3}, \Delta\theta_{n4}]^T \tag{11}$$

Vector of state parameters consisting of temperature beet chips and juice mixture and steam in steam chambers in their respective areas of apparatus;

$$\mathbf{u}(t) = [\Delta G_{n1}, \Delta G_{n2}, \Delta G_{n3}, \Delta G_{n4}]^T \text{ – (12)}$$

vector control, consisting of steam consumption in their respective areas of apparatus;

$$\mathbf{z}(t) = [\Delta\theta_c, \Delta G_c, \Delta G_{\partial c}, \Delta\theta_{\delta}, \Delta\theta_{ж}, \Delta G_{\delta}, \Delta G_{ж}]^T \tag{13}$$

vector of perturbation, where $\Delta G_c, \Delta G_{\partial c}, \Delta G_{\delta}, \Delta G_{ж}$ – expenditure of chips, juice, barometric and pulp water, $\Delta\theta_c, \Delta\theta_{\delta}, \Delta\theta_{ж}$ – chips temperature at the entrance of the diffusion apparatus, barometric and pulp water respectively;

$$\mathbf{y}(t) = [\Delta\theta_1, \Delta\theta_2, \Delta\theta_3, \Delta\theta_4]^T \text{ – (14)}$$

vector of observations (measurements), consisting of a beet chips and juice mixture of temperatures in their respective areas of apparatus.

Then the matrix model (10) have the form:

$$A = \begin{bmatrix} -0.8643 & 0.4667 & 0 & 0 & 0.0259 & 0 & 0 & 0 \\ 0.3678 & -0.8554 & 0.4619 & 0 & 0 & 0.0257 & 0 & 0 \\ 0 & 0.3641 & -0.8467 & 0.4572 & 0 & 0 & 0.0254 & 0 \\ 0 & 0 & 0.3604 & -0.8382 & 0 & 0 & 0 & 0.0251 \\ 11.27 & 0 & 0 & 0 & -11.27 & 0 & 0 & 0 \\ 0 & 25.45 & 0 & 0 & 0 & -25.45 & 0 & 0 \\ 0 & 0 & 20.45 & 0 & 0 & 0 & -20.45 & 0 \\ 0 & 0 & 0 & 13.99 & 0 & 0 & 0 & -13.99 \end{bmatrix}; \tag{15}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 3155.69 & 0 & 0 & 0 \\ 0 & 7351.15 & 0 & 0 \\ 0 & 0 & 5858.90 & 0 \\ 0 & 0 & 0 & 3948.25 \end{bmatrix}, \tag{16}$$

$$G = \begin{bmatrix} 0.3717 & -0.2334 & 0.1299 & 0 & 0 & 0 & 0 \\ 0 & -0.1198 & 0.0342 & 0 & 0 & 0 & 0 \\ 0 & -0.0339 & 0.0254 & 0 & 0 & 0 & 0 \\ 0 & 0.0754 & -0.7293 & 0.2766 & 0.1760 & 0.7712 & 0.7712 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{17}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (18)$$

Algorithm of optimal control. Several algorithms based on or inspired by the ACO metaheuristic have been proposed to tackle continuous optimization problems. One of the most popular ACO-based algorithm for continuous domains is ACOr. Today there are many additions to the classic problem ACOr particular solution to known external disturbances, or given values of vectors x(t) and u(t) in integral quadratic criteria. There are also discrete analogs of these problems.

An interesting variant of the problem ACOr with the introduction of an integrated component on error signal (e = r- y, where r - vector problem, y - vector stabilizing output).

Results and Discussion

Compare discrete system of automatic regulation of the optimal control for diffusion plants, a synthesis algorithm ACOr with the introduction of an integrated component on error signal and no change in the task.

The purpose of the research problem is synthesis of optimal controls, so we used the Control System Toolbox lqi and lqry, realizing set algorithms. For example, take a mathematical model that describes the diffusion zones of temperature settings, and we assume that all measured temperatures, and it is only necessary to stabilize the temperature beet chips and juice mixture reject external disturbances missing.

Lqry function implements a multidimensional array controller type u = -Kx the coordinates of the system while minimizing the criterion:

$$I(\mathbf{u}) = \int_{t_0}^{\infty} (\mathbf{y}^T \mathbf{Q} \mathbf{y} + \mathbf{u}^T \mathbf{R} \mathbf{u}) dt \rightarrow \min_{\mathbf{u}}, \quad (19)$$

Block diagram of the system with the introduction of error signal is shown in Fig. 2 lqi function returns multidimensional optimal regulator type u=-K[x;x$_i$], where x$_i$ – output of the integrator (Fig. 3). Data connectivity features implemented series, feedback and connect.

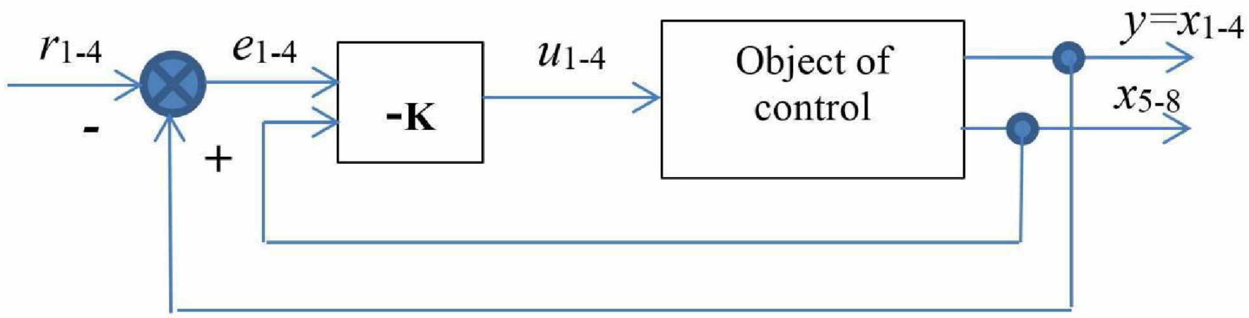

Fig.2. Block diagram of the system with optimal control (algorithm ACOr) and task signal

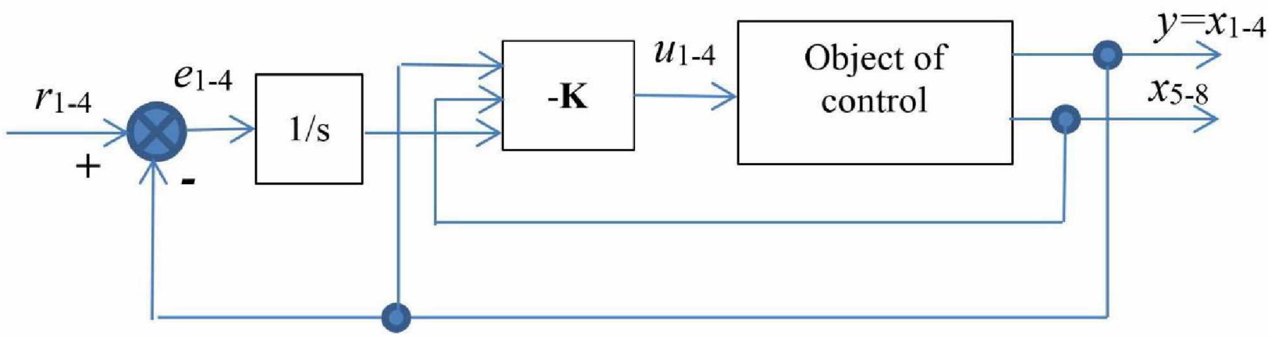

Fig.3. Block diagram of the system with the optimal regulator (ACO$_R$ algorithm) and an integral part of the task signal

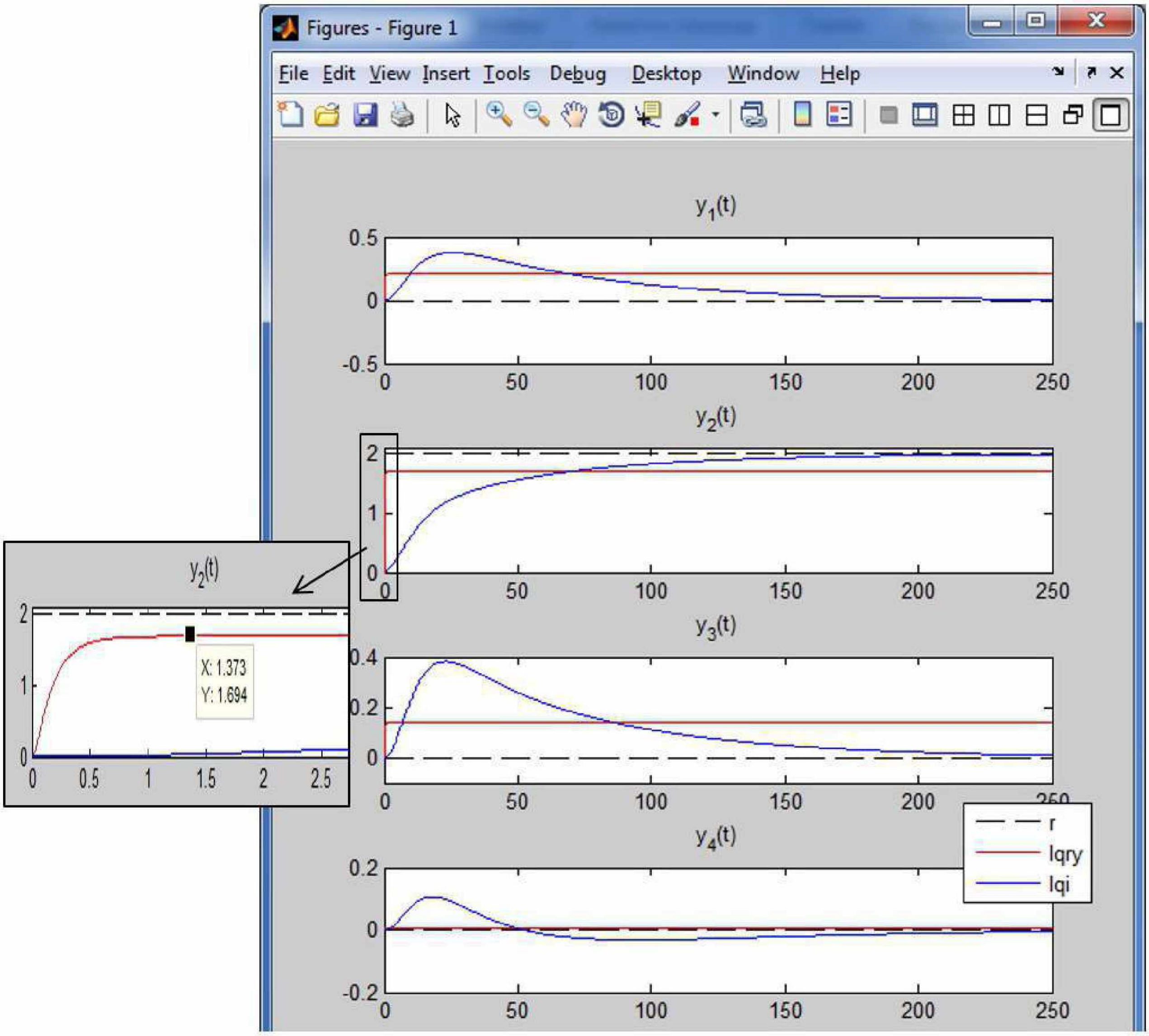

Fig.4. Transient processes with different control algorithms

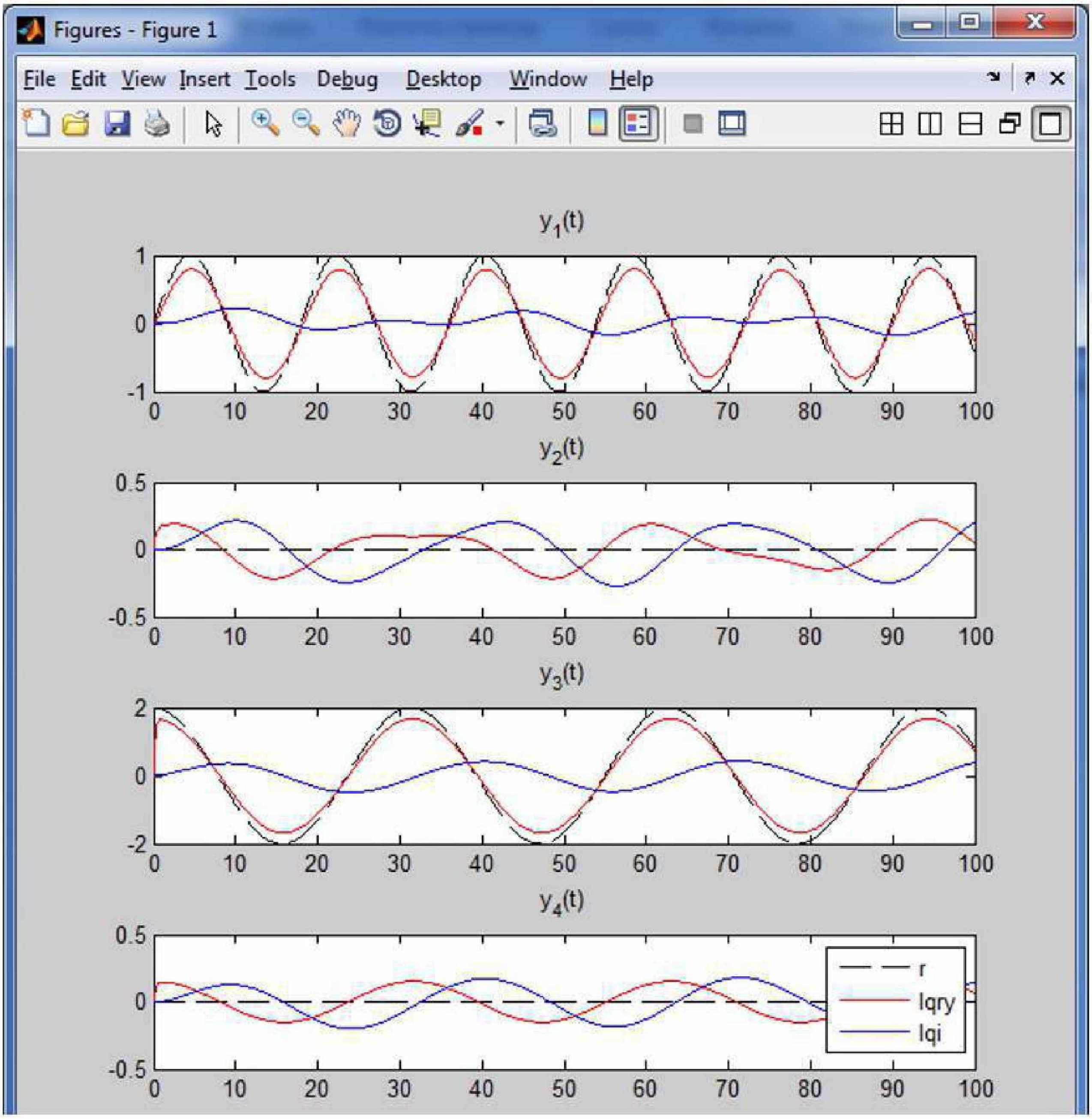

Fig.5. Simulation of system with harmonic task signal

As can be seen from the results (Fig.4. and Fig.5.) of the program at the step change task to a second output using an integrated component of this channel is observed elimination of static errors, although the transition process increases by about 200 times. By cross-linking observed transients on other channels. Also note that the static error for all channels using the algorithm ACOr minimization criterion for outputs does not exceed 0.3 ^{0}C, invested in production schedules (maximum deviation from the set temperature should not exceed 0.5 ^{0}C).

In addition, following the automatic control system optimal regulator with integral component does not have time to work out a signal problem.

Thus, for a given object the feasibility of using multivariate regulator with integral component of outgoing channels is not confirmed. In addition, a closed system optimal control has eigenvalues on the verge of stability, ie to further investigate system for robust stability.

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