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INVESTIGATION OF METHODS FOR IDENTIFYING DYNAMIC CHARACTERISTICS OF CONTROL OBJECTS

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ДОСЛІДЖЕННЯ МЕТОДІВ ІДЕНТИФІКАЦІЇ ДИНАМІЧНИХ ХАРАКТЕРИСТИК ОБ’ЄКТІВ КЕРУВАННЯ

Кобзарев Є.В.

The paper proposes an approach for constructing a mathematical model of a control object, where the transient response of the object is used as the initial data. The advantages of this approach include the use of objective data generated by the control object itself, relative simplicity of implementation, and the ability to obtain an adequate and accurate model due to the utilization of comprehensive dynamic characteristics of the system. In addition, the approach improves identification reliability under conditions of limited experimental data.

The study is aimed at optimizing the considered technological process.

The results show that limiting the order of the differential equation (or transfer function) to the second order significantly simplifies the development of the mathematical model. In some cases, high-order models can be reduced to lower-order models, including first- or second-order ones, without a significant loss of accuracy in describing their characteristics. This can be explained by the following factors: analysis and synthesis tasks are much easier for low-order models; computational accuracy is inversely proportional to the model order; first- and second-order models contain sufficient information for system analysis and synthesis; moreover, increasing the model order does not always improve its accuracy. It is also shown that reducing the model order decreases computational costs and enhances numerical stability.

The obtained identification error is within acceptable limits for this type of problem.

The paper addresses the following issues: selection of the number of points on the step response curve of the control object; choice of an appropriate identification algorithm; determination of point distribution along the curve; and analysis of the influence of the number and placement of points on approximation accuracy. The obtained results can be applied in the design and tuning of automatic control systems.

Keywords: *mathematical model, dynamic characteristics, ammonia production, identification, step response, control object, transient process.*

Introduction. In recent years, global markets have been characterized by a significant increase in raw material prices, which directly leads to higher production costs for domestic industries [1]. In particular, the share of natural gas costs in the total production cost of chemical products currently reaches approximately 75%. Under such conditions, ensuring the competitiveness of Ukrainian manufacturers requires improving the efficiency of raw material and energy resource utilization. This necessitates the optimization of technological processes and control systems. These challenges are especially relevant for ammonia production, which is of considerable importance for the region[1].

Relevance. Ammonia production plays a key role not only in the manufacture of mineral fertilizers but also as a fundamental raw material for various chemical industries. Increasing its efficiency by reducing energy and resource consumption is an important and актуal task. This can be achieved by improving existing control systems or developing new ones, as well as optimizing controller settings.

It should be noted that no mathematical model can fully and accurately represent the behavior of a real physical system. Increasing model accuracy typically requires increasing its complexity, which does not guarantee absolute precision. Therefore, an effective model must balance adequacy and simplicity.

The objective of this study is to investigate methods for identifying control objects using the example of a mathematical model of an ammonia synthesis column, in order to simplify the optimization of dynamic characteristics of automatic control systems[2?3].

Purpose of the study. The aim of this work is to develop an algorithm for identifying control objects based on the least squares method for aperiodic transient processes described by second-order elements with time delay, for the purpose of technological process optimization.

To achieve this goal, the following tasks are addressed:

development of an information-logical structure of relationships between process parameters;

description of the transient response of the control object using a second-order differential equation.

Analysis of studies and publications. Practical experience shows that modernization of technological processes and control systems does not always yield the expected results if controllers at the lower level are improperly tuned. According to literature sources, more than 50% of controllers used in industry are incorrectly adjusted [4-6].

The objects of study include key units of the ammonia synthesis stage: the synthesis column, circulation compressor, separator, and air-cooling apparatus [2].

During the synthesis process, the nitrogen-hydrogen mixture (fresh gas) enters the circulation loop and is directed to the synthesis column, where, in the presence of a catalyst, part of the gas is converted into ammonia. The gas is then cooled, and ammonia is condensed and separated in separators. The unreacted gas is compressed and returned to the cycle. The produced liquid ammonia is stored in specialized high-pressure tanks.

The synthesis column is one of the most complex and critical units in the process. Its reliable operation requires maintaining technological parameters within the limits specified by operational regulations (Fig. 1).

The key control and regulation parameters are pressure, temperature in the catalyst beds, the nitrogen-to-hydrogen ratio in the gas mixture, and the ammonia concentration at the column outlet(Fig. 2).

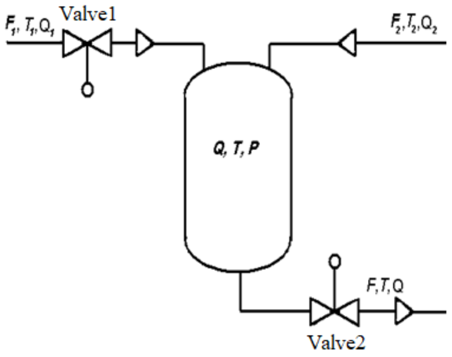

Fig. 1. Ammonia synthesis column

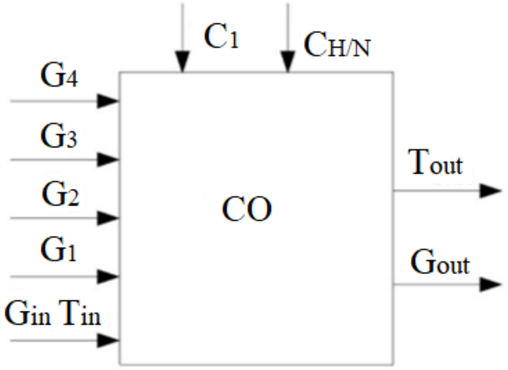

Fig. 2. The synthesis column as a control object:
C1 – ammonia concentration at the inlet;
CH/N – N/H ratio; G1, G2, G3, G4 – flow rates at catalyst beds 1–4; Gin – flow rate at the synthesis column inlet, feed stream; Tin – inlet temperature;
Gout – concentration of the outlet stream;
Tout – outlet temperature

The concentration and temperature of the ammonia at the outlet depend on the concentration, temperature and flow rate of the feedstock at the inlet, the influence of bypass flows, and the ratio of nitrogen (N) to hydrogen (H) flow rates during the process. [7] As the substance passes through each catalyst layer, the temperature between the shelves changes due to heat release during the process; a diagram showing the dependence of outlet temperatures in the catalyst layer on the opening of the control valves is shown in Fig. 3.

Transient processes in controlled systems may be aperiodic or oscillatory in nature. It is known that both types of process can be described with sufficient accuracy by a second-order differential equation.

Let us consider the block diagram of a single-loop automatic control system shown in Fig. 4.

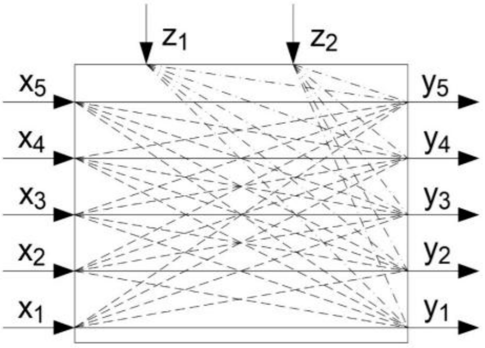

Fig. 3. Block diagram illustrating the relationships between the parameters:
x1, x2, x3, x4 – degree of opening of the actuators on the bypass cold streams; y1, y2, y3, y4 – temperature in the catalyst beds, control parameters;
z1 – ammonia concentration at the inlet;
z2 – ratio of nitrogen N to hydrogen H

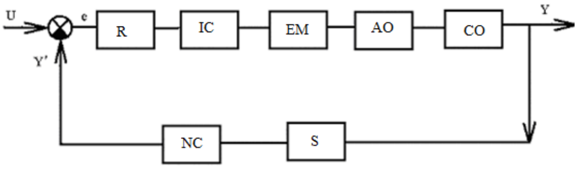

Fig. 4. Block diagram of a single-loop automatic control system:
R – controller; IC – intermediate converter; EM – actuator; AO – control element; CO – controlled object; S – sensor; NC – normalising converter

When recording the acceleration curve on an actual controlled object, we effectively obtain the transient response of an equivalent controlled object (an open-loop system from the intermediate converter to the regulating converter, provided that the transfer function of the secondary instrument is equal to 1). That is, if we identify the equivalent controlled object in the acceleration curve as a second-order system, the functional diagram of a single-loop automatic speed control system can be represented as shown in Fig. 5.

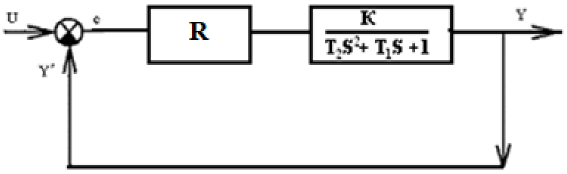

Fig. 5. Modified block diagram of a single-loop automatic control system

The second-order differential equation for the control loop takes the form:

$$(T'')^2 \frac{d^2 y}{dt^2} + T' \frac{dy}{dt} + y = K_p u_0 \qquad (1)$$

T'', T' - control system time constants;
K_p - system transmission ratio;
u_0 - зtask;
y - output signal.

The nature of the transient process in this stage will depend on the magnitude of the ratio $\frac{T'}{T''}$. If $\frac{T'}{T''} \geq 2$, then the transient process will be aperiodic, if $\frac{T'}{T''} < 2$ – oscillating.

Let's find the roots of the differential equation (1):

$$P_{1,2} = -\frac{T'}{2(T'')^2} \pm \sqrt{\left[\frac{T'}{2(T'')^2}\right]^2 - \frac{1}{(T'')^2}} . \qquad (2)$$

If $\frac{T'}{T''} > 2$, the roots of the differential equation P_1 i P_2 will always be positive and negative. The equation for the transfer function will then take the form:

$$y(t) = K_P u_0 \left[1 - \frac{\alpha_2}{\alpha_2 - \alpha_1} \exp(-\alpha_1 t) + \frac{\alpha_1}{\alpha_2 - \alpha_1} \exp(-\alpha_2 t) \right], \qquad (3)$$

where $\alpha_1 = -P_1$, $\alpha_2 = -P_2$;
u_0 - step disturbance

If $\frac{T'}{T''} < 2$ the roots will be complex:

$$P_{1,2} = \alpha_0 \pm j\omega_0, \qquad (4)$$

where $\alpha_0 = \frac{T'}{2(T'')^2}$ – degree of damping of the transient process;

$\omega_0 = \sqrt{\frac{1}{(T'')^2} - \left[\frac{T'}{2(T'')^2}\right]^2}$ – the natural frequency of the system.

In this case, the transfer function is described by the equation:

$$y(t) = K_P u_0 \left[1 - \exp(-\alpha_0 t)(\cos\omega_0 t + \frac{\alpha_0}{\omega_0} \sin\omega_0 t) \right]. \quad (5)$$

Let us consider the identification of control objects using the example of a mathematical model of an ammonia synthesis column calculated theoretically, which has the transfer function (6):

$$W = \frac{e^{-2\cdot s}}{1.5\cdot s^5 + 4\cdot s^4 + 10\cdot s^3 + 10\cdot s^2 + 5\cdot s + 1} \quad (6)$$

We are constructing the fifth-order link response curve with a time delay (Fig. 6).

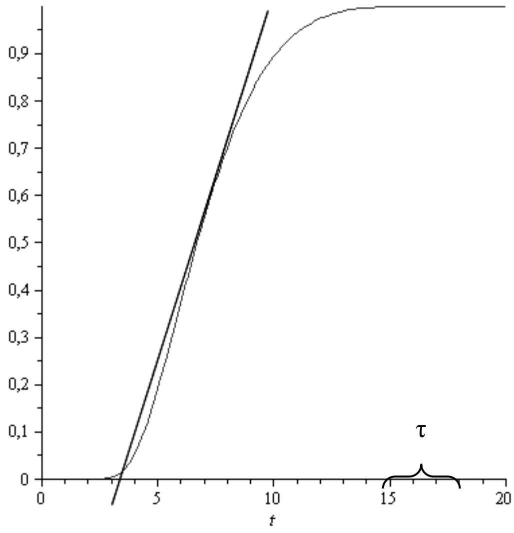

Fig. 6. Крива розгону ланки п’ятого порядку з часом запізнення

Figure 6 shows that the acceleration curve is aperiodic; therefore, equation (3) can be used to derive the equation for the acceleration curve.

The most appropriate approach to determining these variables is the use of the mathematical software package Mathcad.

At the initial stage, the values of the variables α_1 and α_2 are calculated. The obtained results are then substituted into equation (3) in order to derive the transfer function equation. As a result of these substitutions, equation (7) is obtained.

$$y(t) = \Phi(t - 3.505)\cdot(1 - 1.84642\cdot 10^4 \cdot \ell^{-0.553896(t-3.505)} + 1.84632\cdot 10^4 \cdot \ell^{-0.553926(t-3.505)}) \quad (7)$$

Let us plot the response curve of a fifth-order link and the curve corresponding to equation (7) on the same graph.

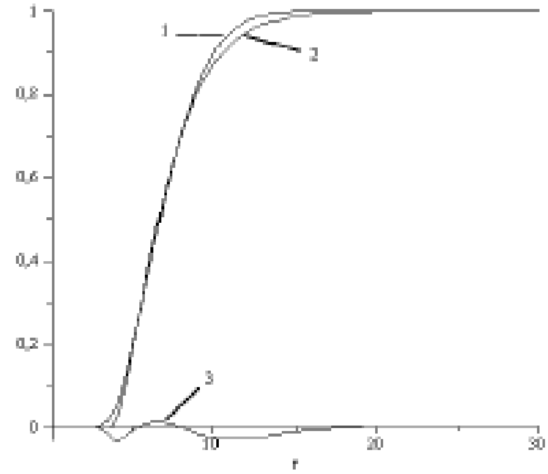

Fig. 7. Initial and obtained response curves of the equivalent object:
1 – response curve of a fifth-order system with time delay; 2 – transient response of a second-order system with time delay; 3 – identification error

Based on the analysis of Fig. 7, it can be concluded that a second-order aperiodic element with time delay provides an adequate approximation of the aperiodic control object with time delay. The maximum deviation between curves 1 and 2 does not exceed 3%. Therefore, in further calculations, it is reasonable to replace the equivalent control object with a second-order element with time delay. To obtain the transfer function (8) [9], the direct Laplace transform of the corresponding equation is performed.

$$W = \frac{1}{3.259\cdot s^2 + 3.611\cdot s + 1} \cdot e^{-3.505 s} \quad (8)$$

Thus, based on the analysis of the points of the step response curve of an aperiodic control object with time delay, it has been established that the application of the least squares method allows the object to be identified with sufficient accuracy as a second-order aperiodic element with time delay. This approach enables the construction of a generalized mathematical model that adequately reflects the main dynamic properties of the real control object.

A key feature of the proposed method is the use of experimentally obtained transient response data, which makes it possible to take into account the real operating conditions of the technological object. The least squares method ensures minimization of the approximation error between the experimental step response and the analytical model representation. This improves identification accuracy without significantly increasing model complexity.

The obtained results indicate that even complex technological control objects characterized by high-order dynamics can be represented with sufficient accuracy by lower-order models. In particular, for aperiodic transient responses, it is advisable to use a second-order model with time delay. This significantly simplifies further analysis and synthesis of automatic control systems.

It is important to emphasize that reducing the order of the mathematical model does not lead to a substantial loss in accuracy of dynamic behavior representation. On the contrary, it often improves numerical stability, reduces computational costs, and simplifies controller tuning procedures. Therefore, second-order models represent an effective compromise between accuracy and simplicity.

The analysis of the obtained results shows that the approximation error between the actual step response and the second-order model with time delay does not exceed acceptable limits and is suitable for engineering calculations. This confirms the applicability of the proposed approach in the design of automatic control systems for complex technological processes, particularly in the chemical industry.

Taking into account the obtained results, it can be concluded that for automatic control systems involving complex multiparameter technological processes, such as an ammonia synthesis column, the equivalent transfer function can be effectively approximated by a second-order aperiodic element with time delay. This significantly simplifies the analysis of dynamic characteristics, as well as the synthesis and optimization of control parameters.

Moreover, the proposed method contributes to improving the efficiency of automatic control systems by enabling the use of simpler yet sufficiently accurate models. This is especially important in industrial applications, where reliability, responsiveness, and cost-efficiency are critical factors.

Conclusions. In this study, an algorithm for identifying control objects based on the least squares method for aperiodic transient processes using second-order models with time delay has been developed and investigated. It has been shown that this approach allows obtaining an adequate mathematical model of the object with relatively low structural complexity.

The results demonstrate that the identification error does not exceed 3%, which is acceptable for this class of problems. This confirms the practical applicability of the proposed method for analysis, synthesis, and optimization of automatic control systems.

The obtained results can be applied in the development and improvement of control systems for technological processes, particularly in ammonia production, as well as in other industrial domains involving complex dynamic systems.

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Кобзарев Є. В Дослідження методів ідентифікації динамічних характеристик об’єктів керування

У роботі запропоновано підхід до побудови математичної моделі об’єкта керування, в якому в якості вихідних даних використовується його перехідний процес. Перевагами запропонованого підходу є використання об’єктивної інформації, сформованої самим об’єктом керування, відносна простота реалізації, а також можливість отримання адекватної та точної моделі завдяки врахуванню узагальнених динамічних характеристик системи керування. Крім того, підхід забезпечує підвищення надійності ідентифікації в умовах обмеженого обсягу експериментальних даних.

Дослідження спрямоване на оптимізацію відповідного технологічного процесу.

У результаті встановлено, що обмеження порядку диференціального рівняння (або передатної функції) другим порядком суттєво спрощує побудову математичної моделі. У ряді випадків моделі високого порядку можуть бути приведені до моделей нижчого порядку — зокрема першого або другого — без істотної втрати точності опису їх характеристик. Це пояснюється тим, що: задачі аналізу та синтезу значно простіші для моделей низького порядку; точність чисельних розрахунків обернено залежить від порядку моделі; моделі першого та другого порядку містять достатній обсяг інформації для дослідження систем; а також тим, що збільшення порядку моделі не завжди призводить до підвищення її точності. Додатково встановлено, що зниження порядку моделі сприяє зменшенню обчислювальних витрат і підвищенню стійкості чисельних процедур.

Отримана похибка ідентифікації знаходиться в допустимих межах для задач такого типу.

У роботі розглянуто такі питання: вибір кількості характерних точок на кривій розгону об’єкта керування; визначення ефективного алгоритму ідентифікації; обґрунтування способу розміщення точок; аналіз впливу кількості та розташування точок на точність апроксимації. Отримані результати можуть бути використані при проєктуванні та налаштуванні систем автоматичного керування.

Ключові слова: *математична модель, динамічні характеристики, виробництво аміаку, алгоритм ідентифікації, крива розгону, об’єкт керування, перехідний процес.*

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