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TRANSITION FUNCTION OF SECOND-ORDER ELEMENT

ABDULLAYEV XAKIM

Namangan State Technical University, Namangan, Uzbekistan
Phone.: (0890) 554-9788, E-mail.: hakim-olim@mail.ru

Abstract: This work analyzes the denominator of the transfer function of second-order elements widely used in modern automatic control systems - the characteristic equation. The transfer function is calculated and derived, and it is proposed to use the expression of this derived transfer function as a mathematical model for the convenience of identification of second-order inertial elements based on experimental transition characteristics.

Keywords: technological process, transfer function, transition function, characteristic equation, time constant, identification, mathematical model, model parameters.

Introduction. In automated control systems for technological processes, production, and their complexes, it is necessary to determine the behavior of the control object, the course of processes occurring in that object, and the patterns in them, as well as to introduce corrections. According to the analysis performed in [1], as a result of such determination and introduction of corrections, the necessity arises to form the influence on the object that ensures good results, that is, when creating control systems for technological processes or industrial objects, the necessity arises to have mathematical descriptions of the control object, control device, and other elements included in this system. Finding the above-mentioned influence belongs to the problems of building a control model based on "input-output" data, i.e., identification problems, and its relevance is clearly visible in the automation of technological processes, production, and their complexes.

Obtaining experimental data related to "input-output" while the object is operating has certain difficulties. In such cases, reference is made to its mathematical model, which allows preliminary study of the object. Mathematical models of objects are differential equations in many cases [2, 3]. In this regard, according to the order of differential equations and the numerical values of parameters in them, objects are divided into 1st-order, 2nd-order inertial, oscillatory, conservative, and other objects [3, 4].

Problem statement. When evaluating the parameters of transition characteristics based on experimental data related to "input-output" of objects, a mathematical model with parameters of these characteristics is selected in advance. Here, it is necessary to select a mathematical model or write it in such a form that finding the parameters of this model from experimental data is convenient.

In practice, identification of the transfer function of first-order inertial elements is more common, which is well covered in [4, 5]. However, in this case, approximation has rough errors. We hope that approximation gives good results for 2nd-order inertial

elements ($\xi = \frac{T_2}{2T_1} > 1$). Here also certain difficulties exist. The transfer function of a

second-order non-oscillatory element is given as follows:

$$h(t) = k + C_1 e^{-s_1 t} + C_2 e^{-s_2 t}$$

The identification of the transfer function of a given element is presented in [5]. This is indeed true, but there is complexity in determining its parameters k, C_1, C_2, s_1, s_2 , for example, this complexity lies in the large number of parameters. In [1, 6], the significant aspects of these parameters for the transition process are shown. If we could write the above transfer function in such a way that the number of parameters decreases, then identification would also be simplified. The problem of this work consists of this.

Methodology and empirical analysis. To solve the problem posed in this work, the mathematical model of the second-order object, the calculated transfer function, characteristic equation, and the transition process in it are analyzed.

The transfer function of this element is:

$$W(p) = \frac{k}{T_1^2 p^2 + T_2 p + 1}. \tag{1}$$

The characteristic equation is:

$$T_1^2 p^2 + T_2 p + 1 = 0. \tag{2}$$

This is a simple quadratic equation. Its roots are found using the following formula:

$$p_{1,2} = \frac{-T_2 \pm \sqrt{T_2^2 - 4T_1^2}}{2T_1^2} \tag{3}$$

Obviously, depending on the magnitude of the expression under the root, the roots will be either real or complex numbers

$$\sqrt{T_2^2 - 4T_1^2}.$$

If the following relationship holds:

$$T_2^2 - 4T_1^2 \geq 0,$$

we can write the following:

$$T_2^2 \geq 4T_1^2. \tag{4}$$

For the damping coefficient:

$$\xi = \frac{T_2}{2T_1} > 1.$$

The 2nd-order element in this case is called an inertial (non-oscillatory) 2nd-order element.

If the following inequality holds for the expression under the root in (3):

$$T_2^2 - 4T_1^2 < 0,$$

the following relationship is obtained for time constants:

$$T_2^2 < 4T_1^2, \tag{5}$$

in this case, the damping coefficient:

$$\xi = \frac{T_2}{2T_1} < 1.$$

The 2nd-order element in this case becomes an oscillatory element.

An ideal oscillatory link is one in which undamped oscillations occur: for it the damping coefficient $\xi=0$.

Obviously, this is possible only if the time constant $T_2 = 0$.

In this case, the oscillatory link becomes a conservative link.

If $T_1 = 0$ is taken for a 2nd-order link, the damping coefficient takes the following value

$$\xi = \infty.$$

This means that the oscillations cannot be fundamental. In this case, a 1st-order aperiodic link is obtained.

The transition processes of a 2nd-order link are calculated according to the representation of its transition function:

$$H(p) = \frac{k}{p(T_1^2 p^2 + T_2 p + 1)}. \quad (6)$$

To find its original, that is, the transition function, it is necessary to factor the expression in parentheses in the denominator of (6). To do this, it is necessary to determine the roots of the characteristic equation (2), which is necessary to determine the relationship between the time constants (4) and (5).

The roots of the characteristic equation for this term are calculated as follows

$$p_1 = \frac{-T_2 \pm \sqrt{T_2^2 - 4T_1^2}}{2T_1^2} = -\alpha_1; \quad p_2 = \frac{-T_2 \pm \sqrt{T_2^2 - 4T_1^2}}{2T_1^2} = -\alpha_2.$$

Obviously, they are real and negative.

According to the factorization rule:

$$T_1^2 p^2 + T_2 p + 1 = T_1^2 (p + \alpha_1)(p + \alpha_2).$$

The image of the transition function can now be written as

$$H(p) = \frac{k}{T_1^2} \frac{1}{p(p + \alpha_1)(p + \alpha_2)}.$$

The following original corresponds to the above image:

$$h(t) = \frac{k}{T_1^2} \frac{1}{\alpha_1 \alpha_2 (\alpha_1 - \alpha_2)} [(\alpha_1 - \alpha_2) + \alpha_2 e^{-\alpha_1 t} - \alpha_1 e^{-\alpha_2 t}]. \quad (7)$$

Let's simplify this expression. To do this, we find the product $\alpha_1 \alpha_2$ separately:

$$\alpha_1 \alpha_2 = \frac{T_2 + \sqrt{T_2^2 - 4T_1^2}}{2T_1^2} * \frac{T_2 - \sqrt{T_2^2 - 4T_1^2}}{2T_1^2} = \frac{T_2^2 - (T_2^2 - 4T_1^2)}{2T_1^4} = \frac{1}{T_1^2} \quad (8)$$

Therefore,

$$\frac{k}{T_1^2} \frac{1}{\alpha_1 \alpha_2} = \frac{k}{T_1^2} T_1^2 = k.$$

In this case, the transition function takes the following form

$$\begin{aligned}
 h(t) &= \frac{k}{(\alpha_1 - \alpha_2)} [(\alpha_1 - \alpha_2) + \alpha_2 e^{-\alpha_1 t} - \alpha_1 e^{-\alpha_2 t}] = \\
 &= k \left[\frac{(\alpha_1 - \alpha_2)}{(\alpha_1 - \alpha_2)} + \frac{\alpha_2 e^{-\alpha_1 t}}{(\alpha_1 - \alpha_2)} - \frac{\alpha_1 e^{-\alpha_2 t}}{(\alpha_1 - \alpha_2)} \right] \\
 &= k \left[1 - \frac{\alpha_2 e^{-\alpha_1 t}}{(\alpha_2 - \alpha_1)} + \frac{\alpha_1 e^{-\alpha_2 t}}{(\alpha_2 - \alpha_1)} \right]. \tag{9}
 \end{aligned}$$

It is clear that expression (9) consists of the sum of two exponentials. Therefore, the second-order link is also called the second-order inertia link, assuming the relation $T_2 \geq 2T_1$ for the above-mentioned time constants.

This conclusion is also supported by the fact that the transfer function of this link can also be represented in the following form:

$$W(p) = \frac{k}{T_1^2} \frac{1}{(p + \alpha_1)(p + \alpha_2)} = \frac{k}{\alpha_1 \alpha_2} \cdot \frac{1}{\frac{1}{\alpha_1} p + 1} \cdot \frac{1}{\frac{1}{\alpha_2} p + 1}.$$

Finally, we can write the following

$$W(p) = \frac{k_1}{\frac{1}{\alpha_1} p + 1} \cdot \frac{k_2}{\frac{1}{\alpha_2} p + 1}. \tag{10}$$

This expression corresponds to the series connection of two inertial links, the time constants of which are written below:

$$T_1 = \frac{1}{\alpha_1}, \quad T_2 = \frac{1}{\alpha_2}, \tag{11}$$

and the amplification coefficients are k_1 and k_2 , respectively, the magnitudes of these coefficients are determined from $k_1 k_2 = k$.

Expression (9) for the transition function can be written as follows, taking into account (11):

$$\begin{aligned}
 h(t) &= \left[\left(k - \frac{k\alpha_2 e^{-\alpha_1 t}}{(\alpha_2 - \alpha_1)} \right) + \left(\frac{k\alpha_1 e^{-\alpha_2 t}}{(\alpha_2 - \alpha_1)} \right) \right] = \\
 &= k \left[\left(1 - \frac{\frac{1}{T_2} e^{-\frac{t}{T_2}}}{\left(\frac{1}{T_2} - \frac{1}{T_1} \right)} \right) + \left(\frac{\frac{1}{T_1} e^{-\frac{t}{T_2}}}{\left(\frac{1}{T_2} - \frac{1}{T_1} \right)} \right) \right] = k \left[\left(1 - \frac{\frac{T_1 T_2}{T_2} e^{-\frac{t}{T_1}}}{\left(\frac{T_1 T_2}{T_2} - \frac{T_1 T_2}{T_1} \right)} \right) + \left(\frac{\frac{T_1 T_2}{T_1} e^{-\frac{t}{T_2}}}{\left(\frac{T_1 T_2}{T_2} - \frac{T_1 T_2}{T_1} \right)} \right) \right] = \\
 &= k \left[\left(1 - \frac{T_1 e^{-\frac{t}{T_1}}}{T_1 - T_2} \right) + \left(\frac{T_2 e^{-\frac{t}{T_2}}}{T_1 - T_2} \right) \right] = \\
 &= k \left(1 - \frac{T_1}{T_1 - T_2} e^{-\frac{t}{T_1}} + \frac{T_2}{T_1 - T_2} e^{-\frac{t}{T_2}} \right).
 \end{aligned}$$

Results. In the transition function of the pre-existing second-order link,

$$h(t) = k + C_1 e^{-s_1 t} + C_2 e^{-s_2 t}$$

k, C_1, C_2, s_1, s_2 are five parameters, which are difficult to identify using the experimental transition characteristic.

The following expression was calculated for the transition function of the second-order link:

$$h(t) = k \left(1 - \frac{T_1}{T_1 - T_2} e^{-\frac{t}{T_1}} + \frac{T_2}{T_1 - T_2} e^{-\frac{t}{T_2}} \right)$$

The resulting expression contains three parameters k, T_1, T_2 . This makes it much easier to determine these parameters from the experimentally given transition characteristic.

Conclusion. In identifying the second-order inertial link ($\xi = \frac{T_2}{2T_1} > 1$) by the experimental transition function, it is proposed to take expression (8) as a mathematical model for the transition function. The identification of the parameters k, T_1, T_2 in this model is relatively easy.

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C O N T E N T S

TECHNICAL SCIENCES: COTTON, TEXTILE AND LIGHT INDUSTRY

Dustkobilov U.	
Circular economy practices in the textile industry: Current status, indicators, and development opportunities	3
Kuldashov G., Oripov J.	
Forecasting the temperature gradient of cotton revolt	10
Kuldashov G., Oripov J.	
Optoelectronic three-wave moisture meter of raw cotton	16
Umarov A.	
Research on the optimization of the saw gin's roll box	26
Tursunov A., Sharibaev N.	
Techniques and devices for mitigating environmental pollution in cotton processing industries	36
Ganikhanov Kh., Mavlyanov A., Abdusamatov A., Mirzaumidov A.	
Effect of the forces on the separation of fiber flow from the saw in an improved lower fiber removal device	43
Nurulloyeva Kh., Abdusamatov A., Mirzaumidov A.	
Experimental determination of the load on the multifaceted columns on the elastic supports of the cotton ginner	49
Muradov A.	
Study of the dynamics of the drive mechanism of moving needles	54
Ismatullayev N., Shamsiyeva M.	
Development of technology for producing leather from african catfish skins	59
Rahmatova S.	
Theoretical study of the quality indicators of newly structured knitted fabrics based on a mathematical model	65
Parpieva N., Kayumov J., Parpiyev D., Lastochkin P.	
Theory of torsional vibrations of grooved cylinders	71
Komilov Sh., Mamadaliyev N., Jurayeva G.	
Quality indicators of cotton fiber analyzed	83

TECHNICAL SCIENCES: AGRICULTURE AND FOOD TECHNOLOGIES

Sobirova M., Mohamed R., Farmonov J., Samadiy M.	
Impact of calcium chloride on the cheese yield during swiss cheese manufacturing process	91

Kurayazov Z., Ravshanov S., Kanoatov X.	
Analysis of the influence of the whitening process during preparation for flouring on the quality of bakery flour made from a mixture of wheat and rye grains	96
Xusanxodjayeva F., Meliboyev M., Ergashev O.	
Development of technology for complex processing of garlic onions	105
Meliboyev M.	
Development of complex processing technology for the secondary mass of watermelons and zucchini	112
Nishonov U., Mominov U.	
Evaluation of organoleptic properties of soft drinks prepared from plant materials	118
Khurmamatov A., Yusupova N., Sarsenbayev N., Mallabayev O.	
Results of determination of bitumen movement modes at different temperatures	124
Yusupova N., Sarsenbayev N., Mallabayev O.	
Results of improving the construction of the plate heat exchange	130

CHEMICAL SCIENCES

Jumayeva D., Zaripbaev K., Oxunjonov Z., Nomonova Z.	
Compositional analysis of raw materials in sorbent production	135
Abdumalikov A., Ummatov O., Mamajonov B., Esonkulova N., Ochilov G.	
Thermal treatment of various samples of low-molecular-weight polyethylene – a by-product of polyethylene production	145
Mamajonova M., Salixanova D., Abduraxmonov E., Ismailova M.	
Energetics of water molecule adsorption on modified bentonite surfaces	153
Abdurahimov A., Abdullayeva F., Usmonova Z.	
Infrared spectroscopic analysis of the purification of sunflower oil from waxy substances using perlite and vermiculite	160
Eshbaeva U., Gökhan Z., Bahri B.	
Theoretical foundations for ensuring the mechanical strength of papers containing collagen hydrolysates	167
Eshbaeva U.	
Research on the printing and technical properties of kraft paper incorporating "cotton cellulose-industrial waste-paculate"	172
Makhkamova D.	
Research on the separation of zinc from metallurgy waste with a mixture of ammonia and ammonium salts	181
Yuldasheva M., Makhkamova D., Turayev Z	188

Study of interaction of components in the H_3BO_3 – KNO_3 – H_2O system	
Juraev M., Siddikov D., Askarova O.	
Aboveground components of salvia sarawschanica	194
Davlatova O.	
Zeolite-based bimetallic composite catalysts for pyrolysis and gasification: chemical technologies for deep biofuel upgrading and conversion intensification	202
Davlatova O.	
Use of BaNaY faujasite zeolite-based bimetallic composite catalysts for deep biofuel purification and selective xylene separation	208
Shamuratova M., Giyasidinov A., Eshmetov I., Nurjanova G.	
On the study of physicochemical properties of soils in the regions of the republic	214
Hoshimov F., Lutpillayeva M.	
Optimized chemical synthesis of stable silver nanoparticles using various reducing and stabilizing agents	220
Sarimsakova N.	
Investigation of the adsorption properties of the sorbent obtained in the process of modification of clinoptilothite in the purification of natural gas from sulfur compounds	227
Kokharov M., Bakhronov Kh., Sultonov A., Jumaeva D., Jumaboeva Z., Gaybullayeva D., Abdumutalova G.	
Adsorption isotherm of hydrogen sulfide on an activated adsorbent derived from hybrid paulownia tomentosa wood	234
Ikramov M., Zakirov B.	
Optimization of the aqueous solubility of monoammonium phosphate, potassium nitrate, and magnesium nitrate via thermodynamic analysis and selective crystallization	243
Nazhimova N., Seitnazarova O.	
Study of the chemical and mineralogical composition of thermal power plant wastes	249

TECHNICAL SCIENCES: MECHANICS AND MECHANICAL ENGINEERING

Berdiev U., Hasanov F., Avazov B., Ostanayev., Viktor M.	
Study of the nature and prospects of practical application of the magnetocaloric effect in energy-efficient cooling systems	256

Sodikov T.	
Research of mechanical part of solar photovoltaic power station	263
Otamirzayev D.	
Calculation of absorption coefficient of organic dye N719 for dye-sensitive solar cell (DSSC)	270
Abdovakhidov M.	
Study on determining the bending and torsional stiffness of packaged working bodies	276
Abdovakhidov M.	
The study torsion fluctuations packet worker organ with provision for influences of the correlation longitudinal acerbity their element	280
Shodmonov J.	
Energy-integrated smart textiles: international trends and prospects for uzbekistan's research ecosystem	285
Djurayev Sh.	
Integrated genetic-differential evolution approach for simultaneous pressure-drop reduction and efficiency enhancement in multi-cyclone dust collectors	292
Mamaxanova Z.	
Technological principles for creating a suit that ensures high reliability and safety in aquatic environments	297
Pirnazarov U.	
Theoretic observation of the cotton movement in the operating camera of the new separator	306
Pirnazarov U.	
Investigation of the interaction between the moving separator screen surface and the cotton mass	315
Yusupov D., Abduraximov D., Muxammadjonov M.	
Determination of energy loss in the magnetic core of oil power transformers under long-term operation conditions	319

ADVANCED PEDAGOGICAL TECHNOLOGIES IN EDUCATION

Abdullayev X.	
Transition function of second-order element	326

ECONOMICAL SCIENCES

Isroilov R.	
Criteria, indicators and laws of small business development	331

Isroilov R.

Concept of assessment of the economic development potential of small business and its evaluation **340**

Bustonov M.

Econometric analysis of the activities of multi-sectoral farms **348**

Bustonov M.

Global digitalization: paths and problems **356**

Kadirova Kh.

Prospects for development and improvement of the mechanism of functioning of the stock market **366**
