Applied Mathematics, 2023, 14, 107-120
https://www.scirp.org/journal/am
ISSN Online: 2152-7393
ISSN Print: 2152-7385

Closed-Loop System Identification Approach of the Inertial Models

Irina Cojuhari

Department of Software Engineering and Automatics, Technical University of Moldova, Chisinau, Republic of Moldova
Email: irina.cojuhari@ati.utm.md

How to cite this paper: Cojuhari, I, (2023) Closed-Loop System Identification Approach of the Inertial Models. *Applied Mathematics*, **14**, 107-120.
https://doi.org/10.4236/am.2023.142006

Received: December 5, 2022
Accepted: February 4, 2023
Published: February 7, 2023

Abstract

The mathematical model that approximates the dynamics of the industrial process is essential for the efficient synthesis of control algorithms in industrial applications. The model of the process can be obtained according to the identification procedures in the open-loop, or in the closed-loop. In the open-loop, the identification methods are well known and offer good process approximation, which is not valid for the closed-loop identification, when the system provides the feedback output and doesn't permit it to be identified in the open-loop. This paper offers an approach for experimental identification in the closed-loop, which supposes the approximation of the process with inertial models, with or without time delay and astatism. The coefficients are calculated based on the values of the critical transfer coefficient and period of the underdamped response of the closed-loop system with P controller, when system achieves the limit of stability. Finally, the closed-loop identification was verified by the computer simulation and the obtained results demonstrated, that the identification procedure in the closed-loop offers good results in process of estimation of the model of the process.

Keywords

Closed-Loop Identification, Mathematical Modelling, Inertial Models, Time Delay, Astatism

1. Introduction

System identification supposes the estimation of the mathematical model of the physical process from observed input/output data and usually is followed by some goals such as system analysis, or automatic control system design [1] [2]. In the automatic control system design, the process models are the core of the synthesis of the control algorithm. The correct synthesis of the control algorithm ensures the stability of the system, disturbance rejection, good robustness and high performance of the control system. The model of the process is essential in the optimal control and in the implementation of the auto-tuning methods of the control algorithm [3] [4].

The analytical methods of synthesis of the control algorithm require to be known the model of the control process. The model of the process can be obtained according to the conservation lows of energy, thermodynamically and other physical and chemical principles. These methods offer so high accuracy, however they are used rarely, due to their complexity and high effort for model process approximation. Opposite to analytical identification is experimental identification, which is based on the experimental data obtained from the process [5] [6] [7]. These methods are widely used in different industrial applications and can be applied in the open-loop, or in the closed-loop.

Open-loop identification methods are simple in use and these methods are applied, if the process dynamics can be linearized around a nominal operating point, and the process is characterized by the non-varied time parameters. There are a lot of identification methods in the open-loop as Vítečková's method, Latzel's method, Harriott's method, Smith's method, Strejc's method, etc., that permit high accuracy to identify different structures of object models with or without time delay, with high or low order inertia [8] [9] [10] [11] [12].

For the case, when a system is identified in the open-loop, the noise signal is not correlated to the input signal, opposite to the closed-loop identification, when the input signal is correlated to the noise signal. In this case, the methods that are efficient in the open-loop identification become biased and not consistent in parameters. Another consideration of using the closed-loop identification is related to the fact that many industrial processes are unstable in the open-loop. Due to unstable behavior of the process, it is required efficient control and stabilization of the process. In this case identification in the open-loop is not acceptable and the only one solution is identification in the closed-loop [13]. Another concern related to the closed-loop identification is the case then process is characterized by the time variable parameters and for implementing the optimal or robust control it is necessary for the model of the process to be periodically re-estimated. In addition, another application of the feedback control is implementation of the auto-tuning methods of the controller, which are realized in many cases based on the closed-loop model estimation [14].

The identification methods in the closed-loop have been developed over 30 years by Gustavsson *et al.* (1977), Söderström and Stoica (1989), Tufa and Ramasamy (2011), Van den Hof (1997), Huang and Shah (1997), Sudhahar et al (2020), Forssell and Ljung (1999) [2] [14] [15] [16] [17] [18].

In process dynamics and control design, the time delay has a central role in the systems. There is a plenty of work for identification of time delay systems in the open and closed-loop, and approaches to approximate the time delay as Pade approximation. However, the presence of a time delay has a big effect on the system stability, system performance, system control, and when the system contains times delay such structures can conduct imprecise models with high bias [10].

Another problem that concerns the open-loop system identification is the case when the system is astatic and in this case, is hard to obtain the mathematical model in the open-loop, and to design the control algorithm. In this case, using the closed-loop system identification can offer possibility to design more efficient the control algorithms for astatic systems [19].

In this paper, it is proposed an approach for system identification in the closed-loop and as a goal, it was proposed the procedure for estimation of the inertial systems with or without time delay, and inertial astatic systems.

Hereinafter, Section 2 introduces the basic of the automatic control systems and the structure of the control algorithm.

Section 3 presents the algorithm for the mathematical identification of the inertial systems with or without time delay and inertial astatic systems, based on the undamped step response of the closed-loop system. Section 4 presents some case studies and computer simulations.

2. Basic Principles of the Automatic Control Systems

The proportional-integral-derivative (PID) control algorithm for the last eight decades has been established as a core of control engineering practices and a vexing problem in many industrial applications remains the problem of determining the tuning parameters of the P, PI or PID controllers [4].

The procedure for synthesis of the PID controller supposes to be known the mathematical model, which approximates the dynamics of the control object, overwise this implies to be used the procedure of experimental identification.

The PID controller as input receives the error signal $e(t)$—between the reference input signal and actual system output signal, and provides command signal—$u(t)$, that is proportional with the sum between the error signal, the integral and derivative error signals, namely [8]:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)\mathrm{d}t + k_d \frac{\mathrm{d}}{\mathrm{d}t} e(t), \tag{1}$$

where $e(t)$—error signal, $u(t)$—command signal, k_p—is the proportional tuning parameter, k_i—integral tuning parameter, k_d—derivative tuning parameter of the PID controller.

The transfer function of the PID controller is given as:

$$H_{\mathrm{PID}}(s) = k_p + \frac{k_i}{s} + k_d s. \tag{2}$$

For the last decades have been developed a big variety of PID tuning techniques in continuous—time, discrete time and frequency domain [4]. In general, these methods can be grouped in the following categories as experimental tuning methods, analytical tuning methods and optimization tuning methods, which are based on the algorithms from artificial intelligence domain.

The experimental methods do not require to be known preliminary the mathematical model, that describes the dynamics of the control object. These methods are based on some simple assumptions for the calculation of the tuning parameters. One of the most known and used experimental methods for tuning the typical controllers is Ziegler-Nichols method, that supposes the calculation of the tuning parameters based on the undamped transient response of the closed-loop system and it does not require to be known the mathematical model of the control object [4].

This method of tuning is performed for the closed-loop systems with PID controller, when the integral tuning parameter—k_i and derivative tuning parameter—k_d, are settled to the zero value. The proportional tuning parameter—k_p is slowly increased until the system reaches the limit of stability and is determinate the period of the oscillations T_{cr}. The value of the proportional tuning parameter, when the system achieves the limit of stability is the critical transfer coefficient—k_{cr}. Based on these two parameters T_{cr} and k_{cr}, there are given the expressions for calculations the tuning parameters of the P, PI and PID controllers.

According to the Ziegler-Nichols method for tuning the P, PI and PID controllers, when system reaches the limit of stability and there are known the critical transfer coefficient and period of the undamped transient response, there are developed the algorithm for experimental identification. According to this algorithm the model parameters are calculated according to the value of the critical transfer coefficient—k_{cr} and period of oscillations—T_{cr}. Based on these two parameters there are proposed the procedure for experimental identification of the model process.

3. Closed-Loop System Identification Approach of the Inertial Models

In order to solve the problem of mathematical identification of the model process, it is proposed a procedure for experimental identification, based on the undamped transient response of the closed-loop control system. According to this algorithm, the process can be approximated with:

- Transfer function with inertia second order and time delay.
- Transfer function with inertia second order and astatism.
- Transfer function with inertia second order, astatism and time delay.

In these cases, the parameters of the model process depend on values of the time delay, natural frequency of the system, critical transfer coefficient and static gain of the system:

$$\text{Parameters} = f\left(\tau, \omega_n, k_{cr}, k\right).$$

3.1. Closed-Loop Identification of the Inertial Model with Time Delay

In order to solve the problem of mathematical identification of the inertial system with time delay, in the closed-loop, it was proposed to approximate the process with the transfer function with inertia second order and time delay:

$$H(s)=\frac{k\mathrm{e}^{-\tau s}}{(T_1 s+1)(T_2 s+1)}=\frac{k\mathrm{e}^{-\tau s}}{a_0 s^2+a_1 s+a_2}=\frac{B(s)}{A(s)}, \tag{3}$$

where T_1, T_2 are time constants; k is a static gain, τ is time delay; $a_0=T_1T_2$, $a_1=T_1+T_2$, $a_2=1$.

The static gain of the system is calculated by [2]:

$$k=\lim_{t\to\infty}\frac{\Delta y}{\Delta u}=\lim_{t\to\infty}\frac{y_{st}-y_{\text{initial}}}{u-u_{\text{initial}}}, \tag{4}$$

where y_{st} is the steady-state output, y_{initial} is the initial value of the output response, u—input signal, u_{inital} is the initial value of the input signal.

From the transfer function (3), the coefficients a_0, a_1, a_2 are proposed to be calculated based on the values of the k_{cr}—critical transfer coefficient and T_{cr}—period of the oscillations, that are obtained for the case, when automatic control system gains the limit of stability. To achieve this state of the system as in the Ziegler-Nichols method, it is considered to be given the closed-loop system with PID controller, where the coefficients k_i, k_d are settled to the zero, and the proportional tuning parameter $k_p > 0$ is varied, until the system achieves the limit of stability.

If it is known the value of period oscillations, it can be calculated the value of the natural frequency by the [2]:

$$\omega_n=\frac{2\pi}{T_{cr}}. \tag{5}$$

The parameters of the model of object (3) are proposed to be calculated in dependency of the natural frequency, value of the critical transfer coefficient, static gain of the system and time delay:

$$a_0, a_1, a_2 = f(\tau, \omega_n, k_{cr}, k).$$

The characteristic equation of the closed-loop system (3) with critical transfer coefficient is the following:

$$A(s)=\left(a_0 s^2+a_1 s+a_2\right)+\mathrm{e}^{-\tau s}k\cdot k_{cr}. \tag{6}$$

Next, it is proposed to make the following substitution in the characteristic Equation (6):

$$s=j\omega_n. \tag{7}$$

Based on the substitution (7) and Euler's formula, the characteristic Equation (6) will become:

$$\begin{aligned} A(j\omega) &= \frac{1}{k}\left(a_0(j\omega_n)^2+a_1(j\omega_n)+a_2\right)+k_{cr}\mathrm{e}^{-\tau\omega_n j} \\ &= \left(-a_0\omega_n^2+a_2+k_{cr}k\cos\tau\omega_n\right)+j\left(a_1\omega_n-k_{cr}k\sin\tau\omega_n\right) \\ &= P(\omega)+jQ(\omega). \end{aligned} \tag{8}$$

Next, it is proposed to equal the real and imaginary parts with zero— $P(\omega)=0$ and $Q(\omega)=0$, and based on these equalling there are obtained the following expressions for calculation the model parameters:

$$\begin{cases} a_0 = \dfrac{a_2 + k_{cr} k \cos \tau\omega_n}{\omega_n^2}; \\ a_1 = \dfrac{k_{cr} k \sin \tau\omega_n}{\omega_n}; \\ a_2 = 1. \end{cases} \tag{9}$$

Based on Equation (9), the parameters of the inertial model with time delay are calculated in dependency of the natural frequency, critical transfer coefficient and static gain value.

3.2. Closed-Loop Identification of the Inertial Astatic Model

Many processes can be described by the models with inertia and astatism. In the open-loop so kind of systems are identified with difficulties, due to the step response of the system. Next, it is proposed the procedure for approximation of the inertial astatic process with the model of the object with inertia second order and astatism:

$$H(s) = \frac{k}{s(T_1 s + 1)(T_2 s + 1)} = \frac{k}{a_0 s^3 + a_1 s^2 + a_2 s} = \frac{B(s)}{A(s)}, \tag{10}$$

where T_1, T_2 are time constants; k is static gain of the system, that is calculated according to Equation (4); $a_0 = T_1 T_2$, $a_1 = T_1 + T_2$, $a_2 = 1$.

The coefficients a_0, a_1, a_2 are proposed to be calculated in dependency of the parameters, that are obtained from the undamped transient response of the closed-loop system:

$$a_0, a_1, a_2 = f(\omega_n, k_{cr}, k). \tag{11}$$

The natural frequency of the system is determinate according to Equation (5).

The characteristic equation of the closed-loop system (10) is the following:

$$A(s) = \frac{1}{k}\left(a_0 s^3 + a_1 s^2 + a_2 s\right) + k_{cr}. \tag{12}$$

According to the identification procedure, it is used the substitution (7), and characteristic equation becomes:

$$\begin{aligned} A(j\omega) &= \frac{1}{k}\left(a_0 (j\omega_n)^3 + a_1 (j\omega_n)^2 + a_2 (j\omega_n)\right) + k_{cr} \\ &= \left(-a_1\omega_n^2 + k_{cr} k\right) + j\left(-a_0\omega_n^3 + a_2\omega_n\right) \\ &= P(\omega) + jQ(\omega). \end{aligned} \tag{13}$$

Next, the real and imaginary parts are equalling with zero and there are obtained the following equations for calculation the model parameters:

$$\begin{cases} a_0 = \dfrac{1}{\omega_n^2}; \\ a_1 = \dfrac{k_{cr}k}{\omega_n^2}; \\ a_2 = 1. \end{cases} \tag{14}$$

3.3. Closed-Loop Identification of the Inertial Astatic Model with Time Delay

Next, it is proposed the procedure of the closed-loop identification of the inertial model with time delay and astatism:

$$H(s) = \frac{k\mathrm{e}^{-\tau s}}{s(T_1 s+1)(T_2 s+1)} = \frac{k\mathrm{e}^{-\tau s}}{a_0 s^3 + a_1 s^2 + a_2 s} = \frac{B(s)}{A(s)}, \tag{15}$$

where T_1, T_2 are time constants; k is static gain, that is calculated according to Equation (4), τ is time delay; $a_0 = T_1T_2$, $a_1 = T_1 + T_2$, $a_2 = 1$.

The parameters of the model process (15) are proposed to be estimated in dependency of the parameters:

$$a_0, a_1, a_2 = f(\tau, \omega_n, k_{cr}, k), \tag{16}$$

where the natural frequency ω_n is determinate according to the Equation (5), k—according to Equation (4) and τ—time delay is determine from undamped transient response of the system.

The characteristic equation of the closed-loop system (15) with critical transfer coefficient is the following:

$$A(s) = \left(a_0 s^3 + a_1 s^2 + a_2 s\right) + \mathrm{e}^{-\tau s} k \cdot k_{cr}. \tag{17}$$

Based on the substitution (7) and Euler's formula, the characteristic Equation (17) becomes:

$$\begin{aligned} A(j\omega) &= \frac{1}{k}\left(a_0 (j\omega_n)^3 + a_1 (j\omega_n)^2 + a_2 (j\omega_n)\right) + k_{cr}\mathrm{e}^{-\tau\omega_n j} \\ &= \left(-a_0\omega_n^2 + k_{cr}k\cos\tau\omega_n\right) + j\left(-a_0\omega_n^3 + a_2\omega_n - k_{cr}k\sin\tau\omega\right) \\ &= P(\omega) + jQ(\omega). \end{aligned} \tag{18}$$

Next, it is proposed to equal the real and imaginary parts with zero— $P(\omega) = 0$ and $Q(\omega) = 0$, and based on these equalling there are obtained the following expressions for calculation the model parameters

$$\begin{cases} a_0 = \dfrac{a_2\omega_n - k_{cr}k\sin\tau\omega_n}{\omega_n^3}; \\ a_1 = \dfrac{k_{cr}k\cos\tau\omega_n}{\omega_n^2}; \\ a_2 = 1. \end{cases} \tag{19}$$

3.4. Algorithm for Closed-Loop Identification of the Inertial Models

Based on the proposed approach for closed-loop identification of the inertial models, there is presented an algorithm for experimental identification, that consists of the following stages:

1) Preliminary information gathering of the process, which supposes determination of the process type: fast or slow, with or without time delay, astatic system, or inertial system.

2) Establishment of the feedback control system with P controller.

3) The proportional tuning parameter $k_p > 0$ is varied, until the system achieves the limit of stability and it is determinate the value of static gain k_{cr}.

4) From the undamped transient response of the closed-loop system there are determinate: period of oscillations—T_{cr}; time delay—τ; static gain—k.

5) Based on the value of the oscillation period, there is calculated the value of natural frequency of the system, according to Equation (5) and the value of the static gain according to Equation (4).

6) There is chosen the model process and is estimated its parameters in correspondence with Table 1.

7) Model validation, that is important step in system identification and it tests amount to computing the model residuals.

In Table 1, there are presented the analytical expressions for calculation of the parameters of transfer function, which approximates the dynamics of the process.

4. Applications and Computer Simulation

4.1. Identification of the Inertial Model with Time Delay

It is considered, that the process is described by the transfer function with inertia third order and time delay:

$$H(s) = \frac{e^{-10s}}{30s^3 + 31s^2 + 10s + 1} = \frac{B(s)}{A(s)}. \tag{20}$$

Table 1. Expressions for identification the model object's parameters, based on the undamped response of the closed-loop system.

No.	Model process	Transfer function	Expressions for calculation the model object's parameters
1	Transfer function with inertia second order and time delay	$H(s) = \frac{ke^{-\tau s}}{(T_1 s+1)(T_2 s+1)}$	$a_0 = \frac{a_2 + k_{cr} k \cos \tau\omega_n}{\omega_n^2}$; $a_1 = \frac{k_{cr} k \sin \tau\omega_n}{\omega_n}$; $a_2 = 1$.
2	Transfer function with inertia second order and astatism	$H(s) = \frac{k}{s(T_1 s+1)(T_2 s+1)}$	$a_0 = \frac{1}{\omega_n^2}$; $a_1 = \frac{k_{cr} k}{\omega_n^2}$; $a_2 = 1$.
3	Transfer function with inertia second order, astatism and time delay.	$H(s) = \frac{ke^{-\tau s}}{s(T_1 s+1)(T_2 s+1)}$	$a_0 = \frac{a_2\omega_n - k_{cr} k \sin \tau\omega_n}{\omega_n^3}$; $a_1 = \frac{k_{cr} k \cos \tau\omega_n}{\omega_n^2}$; $a_2 = 1$.

The automatic control system with a respective model of object with P controller was simulated in MATLAB and according to the proposed method of identification, the k_i, k_d tuning parameters were settled to zero, and the proportional tuning parameter $k_p > 0$ was varied until it was achieved the undamped transient response, for the value of critical transfer coefficient: $k_{cr} = 1.533$.

From the undamped transient response of the closed-loop system, there are obtained the following parameters (**Figure 1**):

$$T_{cr} = 37.75\ \text{s},\ \tau = 10\ \text{s},\ \omega_n = 0.1664.$$

According to the obtained values, based on Equation (9), there are calculated the model parameters: $a_0 = 30.92, a_1 = 9.1719, a_2 = 1$. Thus, the identified transfer function of the process is:

$$H(s) = \frac{e^{-10s}}{30.92s^2 + 9.17s + 1} = \frac{B(s)}{A(s)}. \tag{21}$$

In the **Figure 2**, it is presented two system outputs: curve 1—the step response of the given transfer function (20); curve 2—the step response of the identified model (21).

4.2. Identification of the Inertial Astatic Model

The process is described by the transfer function with inertia second order and astatism:

$$H(s) = \frac{1}{s(6s^2 + 5s + 1)} = \frac{B(s)}{A(s)}. \tag{22}$$

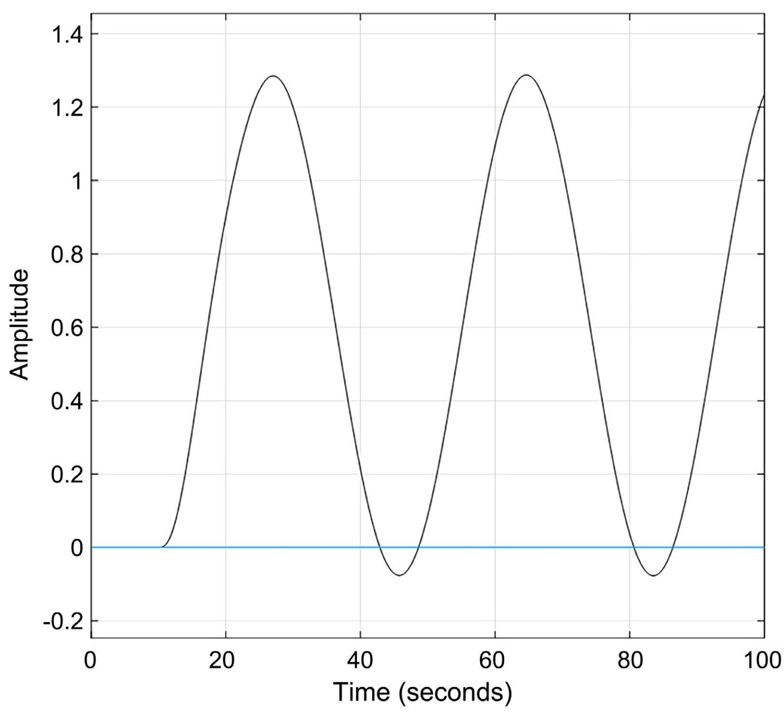

Figure 1. Undamped step response of the closed-loop system.

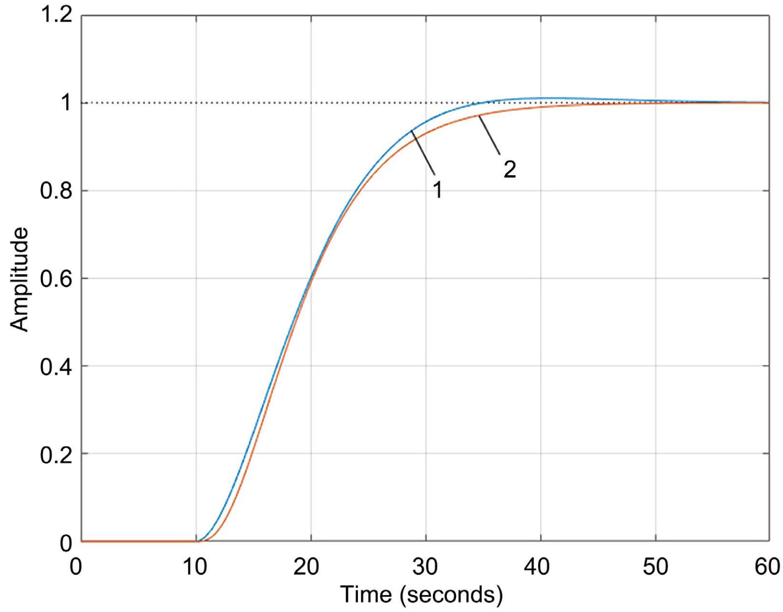

Figure 2. Comparison of the system step responses: 1—step response of the original model (20); 2—step response of the identified model (21).

The closed-loop system with P controller was brought to the limit of stability (**Figure 3**) and from **Figure 3**, there are obtained the parameters:

$$k_{cr} = 0.83,\ T_{cr} = 15.339\ \text{s}.$$

The value of natural frequency of the system, it was calculated according to Equation (5):

$$\omega_n = \frac{2\pi}{T_{cr}} = 0.4096.$$

According to the obtained values, based on Equation (14), there are calculated the transfer function of the astatic system with inertia:

$$H(s) = \frac{1}{s(5.95s^2 + 4.94s + 1)} = \frac{B(s)}{A(s)}. \tag{23}$$

For verification of the obtained results, it was done the comparison of the system output (22) with output from the identified model (23), presented in **Figure 4**, that can be observed that the outputs coincide and the obtained model approximate with high accuracy the astatic inertial system.

4.3. Identification of the Inertial Astatic Model with Time Delay

It is considered that process to be described by the transfer function with inertia second order, time delay and astatism:

$$H(s) = \frac{e^{-20s}}{s(50s^2 + 15s + 1)} = \frac{B(s)}{A(s)}. \tag{24}$$

According to the identification procedure, it was obtained the undamped transient response of the system, **Figure 5** and obtained parameters are:

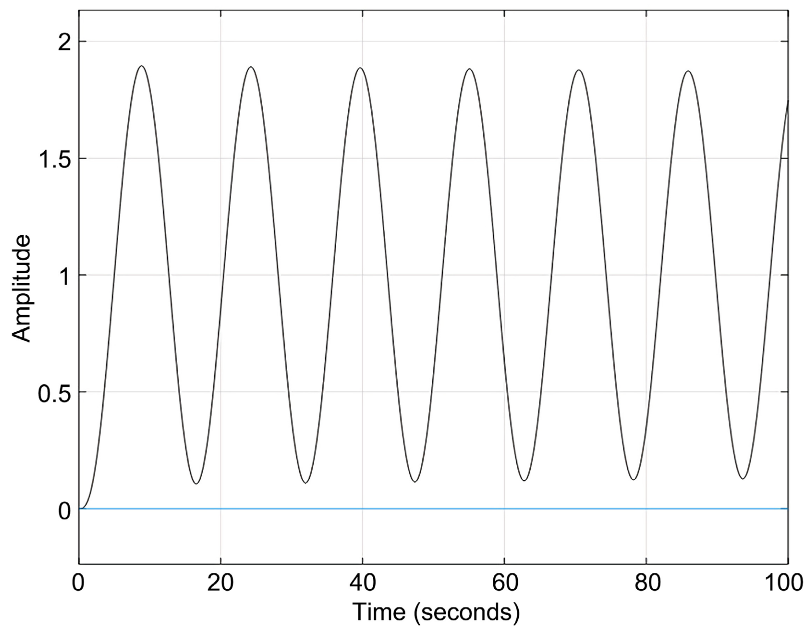

Figure 3. Undamped step response of the closed-loop system.

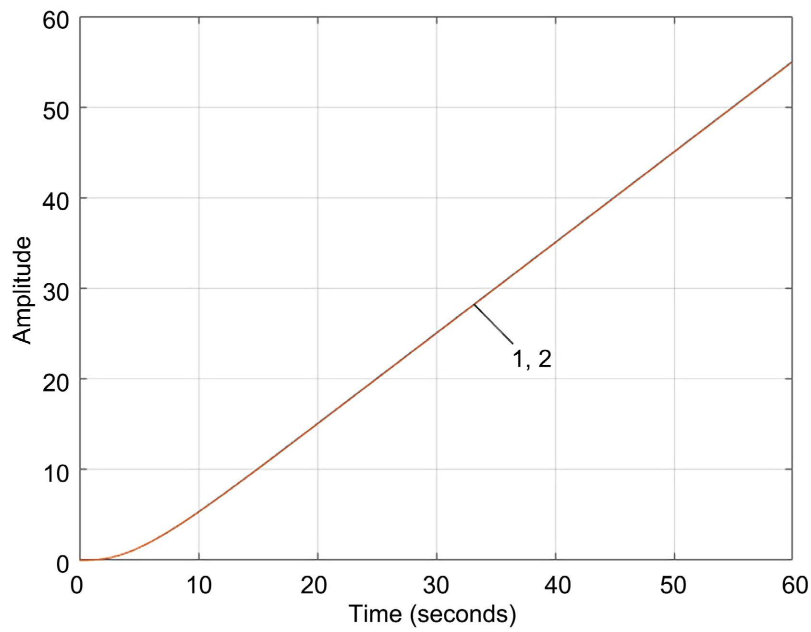

Figure 4. Step responses of the system: 1—original model (22); 2—identified model (23).

$$k_{cr} = 0.052,\ T_{cr} = 137\ \text{s},\ \tau = 20\ \text{s}.$$

The value of natural frequency was calculate based on (5) relationship and there is obtained:

$$\omega_n = 0.0459\ .$$

According to the obtained values of natural frequency, critical transfer coefficient, based on Equation (19), there are calculated the model parameters: $a_0 = 47.46$, $a_1 = 15.03$, $a_2 = 1$.

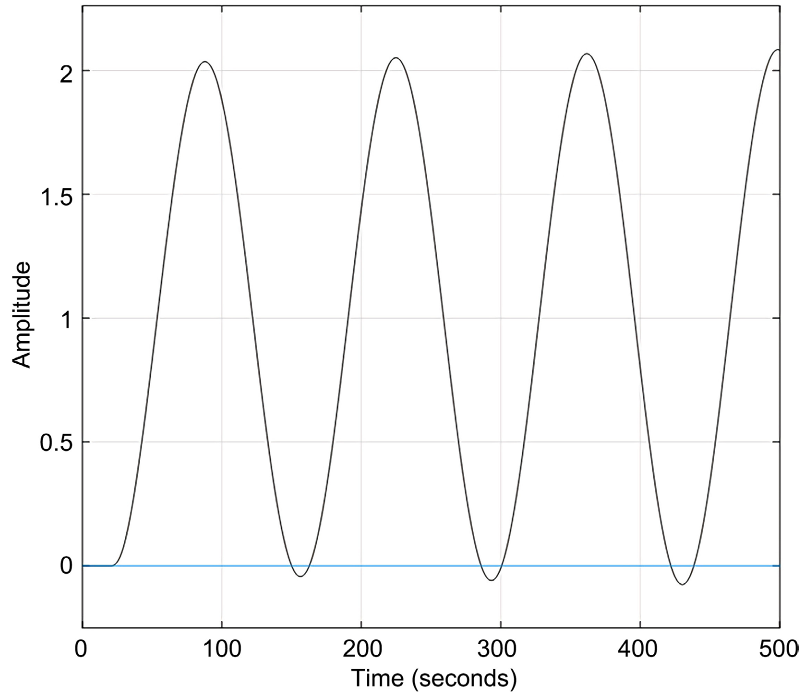

Figure 5. Undamped step response of the closed-loop system.

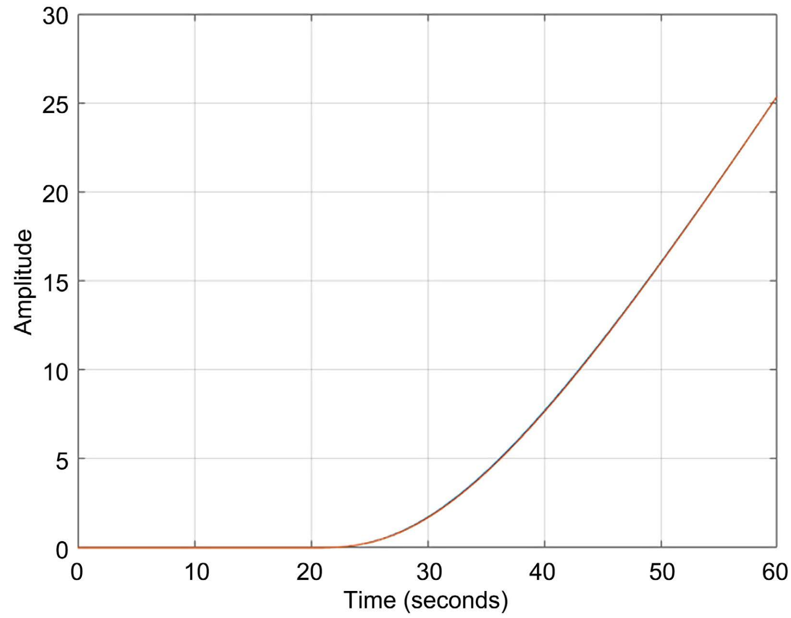

Figure 6. Comparison of the step responses.

Thus, the identified transfer function of the process is:

$$H(s) = \frac{e^{-20s}}{s\left(47.46s^2 + 15.03s + 1\right)} = \frac{B(s)}{A(s)}. \tag{25}$$

In **Figure 6**, it is presented the comparison of system outputs of the given transfer function (24) and identified model (25).

From **Figure 6**, it can be observed, that the system outputs coincide.

5. Conclusions

In this paper, it was developed an algorithm for experimental identification in the closed-loop of the inertial systems with or without time delay, and astatic systems with or without time delay. The algorithm supposes to be achieved the limit of stability of the closed-loop system and based on the parameters, that are obtained from the undamped response of the system, there are presented some simple expressions for the calculation of the parameters of the model.

The closed-loop identification was verified by computer simulation and the obtained simulated results demonstrate that the identification procedure in the closed-loop offers good results in process of estimating the model process in the closed-loop and this method can be used as an application for the synthesis of the auto-tuning PID algorithms.

Acknowledgements

This research was funded by the postdoc project "Models and algorithms for control and behavior approach of the interoperable systems", No. 22.00208.5007.12/PD I, running at the Technical University of Moldova.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Park, M.S., Yang, D.H., Park, D.G. and Hong, S.K. (2003) An Experimental Study on the Closed-Loop System Identification by Observer/Controller Identification (OCID) Algorithm. *Proceedings of* 2003 *IEEE Conference on Control Applications*, Istanbul, 25 June 2003, 37-42.

[2] Forssell, U. and Ljung, L. (1999) Closed-Loop Identification Revisited. *Journal of IFAC Automatica*, **35**, 1215-1241. https://doi.org/10.1016/S0005-1098(99)00022-9

[3] Hornsey, S. (2018) A Review of Relay Auto-Tuning Methods for the Tuning of PID-Type Controllers. *An International Journal of Undergraduate Research*, **11**, 1-1.1.

[4] O'Dwyer, A. (2009) Handbook of PI and PID Controller Tuning Rules. 3rd Edition, Imperial College Press, London. https://doi.org/10.1142/p575

[5] Ertveldt, J., Sanchez-Medina, J., Jardon, Z., Hinderdael, M. and Guillaume, P. (2022) Experimental Identification of Process Dynamics for Real-Time Control of Directed Energy Deposition. *Procedia CIRP*, **111**, 321-325. https://doi.org/10.1016/j.procir.2022.08.031

[6] Kalil, C., de Castro, M., Silva, D. and Cortez, C. (2021) Applying Graph Theory and Mathematical-Computational Modelling to Study a Neurophysiological Circuit. *Open Journal of Modelling and Simulation*, **9**, 159-171. https://doi.org/10.4236/ojmsi.2021.92011

[7] Ebadat, A. (2017) Experiment Design for Closed-Loop System Identification with Applications in Model Predictive Control and Occupancy Estimation. Doctoral Thesis, KTH Royal Institute of Technology, Stockholm.

[8] Linder, J. and Enqvist, M. (2017) Identification of Systems with Unknown Inputs Using Indirect Input Measurements. *International Journal of Control*, **90**, 729-745. https://doi.org/10.1080/00207179.2016.1222557

[9] Herrera, J., Ibeas, A., De la Sen, M., Alcántara, S. and Alonso-Quesada, S. (2013) Identification and Control of Delayed Unstable and Integrative LTI MIMO Systems Using Pattern Search Methods. *Advances in Difference Equations*, **2013**, 331. https://doi.org/10.1186/1687-1847-2013-331

[10] Acioli Júnior, G., João, B.M. and Santos, Barros, P.R. (2009) On Simple Identification Techniques for First-Order plus Time-Delay Systems. *IFAC Proceedings*, **42**, 605-610. https://doi.org/10.3182/20090706-3-FR-2004.00100

[11] Laskawski, M.S. and Kazala, R. (2018) Identification of Parameters of Inertial Models Using the Levenberg-Marquardt Method. *Proceedings of the* 2018*th Conference on Electrotechnology*: *Processes*, *Models*, *Control and Computer Science* (*EPMCCS*), Kielce, 12-14 November 2018, 1-5. https://doi.org/10.1109/EPMCCS.2018.8596396

[12] Muroi, H. and Adachi, Sh. (2015) Model Validation Criteria for System Identification in Time Domain. *IFAC-Papers onLine*, **48**, 86-91. https://doi.org/10.1016/j.ifacol.2015.12.105

[13] Huang, B. and Shah, S.L. (1997) Closed-Loop Identification: A Two Step Approach. *Journal of Process Control*, **7**, 425-438. https://doi.org/10.1016/S0959-1524(97)00019-X

[14] Tufa, L.D. and Ramasamy, M. (2011) Closed-Loop Identification of Systems with Uncertain Time Delays Using ARX-OBF Structure. *Journal of Process Control*, **21**, 1148-1154. https://doi.org/10.1016/j.jprocont.2011.06.021

[15] Van den Hof, P. (1997) Closed-Loop Identification. *IFAC Proceedings Series*, **3**, 1547-1560. https://doi.org/10.1016/S1474-6670(17)43063-1

[16] Wang, J.H. and Ramirez-Mendoza, R.A. (2020) The Practical Analysis for Closed-Loop System Identification. *Cogent Engineering*, **7**, Article ID: 1796895. https://doi.org/10.1080/23311916.2020.1796895

[17] Sharma, S., Verma, B. and Padhy, P.K. (2022) Closed-Loop Identification of Stable and Unstable Processes with Time-Delay. *Journal of the Franklin Institute*, **359**, 3313-3332. https://doi.org/10.1016/j.jfranklin.2022.03.006

[18] Padma Sree, R. and Chidambaram, M. (2006) Improved Closed Loop Identification of Transfer Function Model for Unstable Systems. *Journal of the Franklin Institute*, **343**, 152-160. https://doi.org/10.1016/j.jfranklin.2005.10.001

[19] Kurek, J. (2013) Identification of Inertial Model for Astatic System. *Proceedings of the* 18*th International Conference on Methods & Models in Automation & Robotics* (*MMAR*), Miedzyzdroje, 26-29 August 2013, 692-695. https://doi.org/10.1109/MMAR.2013.6669995