A Novel Delay-Based Control Algorithm: Experimental Application to an Electromechanical System

Necdet Sinan Özbek[1, 2], *İlyas Eker*[2]

[1]Department of Electrical and Electronics Engineering, Adana, Turkey
nozbek@adanbtu.edu.tr, nsinanozbek@gmail.com
[2]Department of Electrical and Electronics Engineering, Çukurova University, Adana, Turkey
ilyas@cu.edu.tr

Abstract— **This study addresses a modified delay-based control structure for a second order linear time-invariant system. Further, experimental applications validate the theoretical results. From a practical point of view, this study presents an alternative control structure to obtain better control performance in the presence of measurement noise as well as uncertainties.**

Keywords—delay-based control; electromechanical system; experimental application; proportional integral derivative control; stability

1. Introduction

A number of sources such as transportation, communication, and computation may cause a time delay in the design, analysis, and synthesis of various control applications, for instance, networked control systems, engine control, and teleoperation of robots [1]–[3]. Further, delay effects on system dynamics and closed-loop control performance can be quite complex. For instance, an appropriate time-delay value in the feedback control system may improve the performance of the controlled system, while the excessive use of the time delay may cause detrimental effects on the system performance or even cause instability of the overall closed loop system. With this in mind, a tremendous amount of research effort has been devoted to understand and clarify the effects of delay on control systems.

Contrary to the detrimental effects of time delay, an intentional time delay, in some cases, presents an opportunity to increase the closed loop control performance when appropriately incorporated into the control system. This idea has been elaborated in a number of studies in control society. For instance, Suh *et al.* [4], [5], address a proportional minus delay control structure. Another study focuses on the favourable effects of time delay for handling uncertainties [6]. A further study highlights that a delayed positive feedback can stabilize an oscillatory system [7]. Yet another advantage of delay term is that one can use delay instead of derivative, which may improve the closed-loop control performance without any estimation for derivative terms [8]–[11]. Further, some studies use the time delay action in state feedback control scheme to approximate integral and derivative terms [12], [13]. Zalluhoglu *et al.* propose different types of delayed feedback control schemes for Rijke tube thermoacoustic instability problem [14]. In that study, cluster treatment of characteristic roots (CTCR) is utilized to meet the objectives. In a recent work, it is stated that the disturbance rejection capability of a single input single output (SISO) system can be improved by utilizing an appropriate delay value [15]. Apart from these studies, a number of recent studies indicate that a deliberate introduction of the delay in the controller may help to design effective and simple control strategy [8]–[11]. The control scheme enables us the implementation of the controller without any additional filter, which preserves both simplicity and control cost. Furthermore, satisfactorily performance can be achieved if the noise levels are low [11], [16], [17].

A number of studies on the analysis and design of delay-based controllers can be summarized as follows. In [4], Suh and Bien address a proportional minus delay controller, which attenuates high frequency noise by performing an averaged derivative action over a finite period. A novel-PI type controller with a delayed filtered integral action is presented in [18]. A further study elaborates a delay type PID controller comprising delayed integral and derivative terms [19]. However, stability issues are not addressed in that study. Concerning to this matter, the stability analysis and tuning strategy of a proportional retarded (PR) control scheme is firstly addressed in [9], wherein simple tuning rules for assigning the dominant poles. According to the results, the PR controller outperforms classical proportional derivative (PD) controller in terms of tracking performance and control signal quality. A further benefit of the PR control strategy is that its numerical realization is computationally more efficient than other classical control techniques such as PID controller. In [10], further results are addressed for a proportional integral retarded (PIR) control scheme, wherein the stability analysis is derived in the sense of the algebraic geometric analysis. The control structure is depicted in Fig.1. Analytical tuning strategies are discussed in [10], [20]. A further discussion on delay-based control design techniques is presented in [21]. That study also presents a real-time application for an electrometrical system, which frequently used in various industrial control applications. Further, a position control problem of servo drives is elaborated by using a cascade proportional integral retarded control [22]. The aforementioned studies present explicit analytical tuning strategy containing a dominant triple root assignment with the aim of producing the maximum exponential decay rate of the closed-loop system. From a different perspective, a geometrical approach for a proportional delayed controller is highlighted in [23].

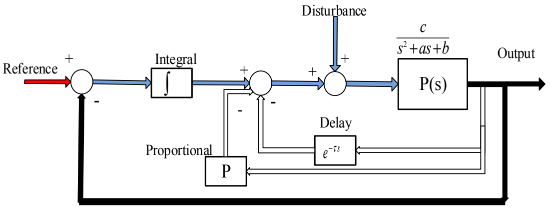

Fig. 1. Proportional Integral Retarded controller [10]

By inspiring from the aforementioned studies, the present study explores such an idea in control of an electromechanical system represented by second order transfer function. Although we employ the general methodology introduced by Villafuerte *et al.*, a new control scheme, namely, Proportional Integral- Proportional Retarded controller is investigated. In this control scheme, a further modification of retarded type controller is presented. Based on this, we combine a PI controller and PR control scheme to control second order systems.

The present study is organized as follows. The second section is dedicated to the experimental set-up and model development of the electromechanical system. The third section addresses the fundamental mathematical concepts, the related theoretical background, and the design procedure of the proposed control scheme. The fourth section illustrates a number of simulation and real-time experimental results. Finally, the last section presents some concluding remarks and future works.

2. Preliminaries and Experimental Set-up

2.1. Modelling of the Process

Generally, designing a high performance control system necessitate a proper system model. Towards this goal, this section elaborates modelling and identification of a DC motor. The schematic diagram is depicted in Fig.2.

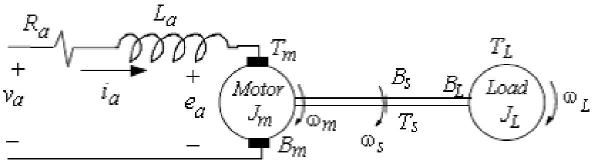

Fig. 2. Electromechanical system [21], [24]

The dynamical equation of the electromechanical system can be modelled as follows [24]–[26].

$$v_a(t) = L_a \frac{d}{dt} i_a(t) + R_a . i_a(t) + K_m \omega_m(t) \qquad (1)$$

$$J_m \left(\frac{d}{dt} \omega_m(t) \right) = T_m(t) - T_s(t) = R_m \omega_m(t) - T_f(\omega_m) \qquad (2)$$

$$T_s(t) = k_s(\theta_m(t) - \theta_L(t)) - B_s(\omega_m(t) - \omega_L(t)) \qquad (3)$$

$$\frac{d}{dt}\theta_m(t) = \omega_m(t), \frac{d}{dt}\theta_L(t) = \omega_L(t) \qquad (4)$$

where

Table 1. DC motor parameters

DC Motor Parameters			
v_a	Armature voltage	R_M, R_L	Viscous friction,
L_a	Armature inductance,	K_M	Torque coefficient,
R_a	Armature resistance,	T_M	Generated motor torque,
i_a	Armature current,	T_d	External load disturbance,
T_s	Nonlinear friction,	T_f	Transmitted shaft torque,
J_m, J_L	Moments of inertia,	ω_m, ω_L	Rotational speeds

Table 1 presents the DC motor parameters. The block diagram of the system is given in Fig. 3.

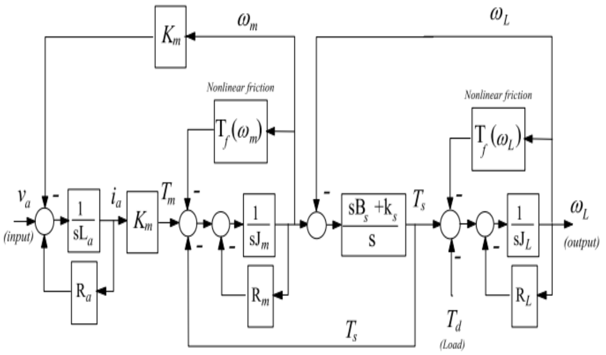

Fig. 3. Block diagram of the electromechanical system [24], [27]

2.2. Experimental Procedure

The experimental setup is linked to the computer by a data acquisition (DAQ) board in order to carry out real-time applications. The described experiments need the Matlab/Simulink® based real-time xPC target software is used as a software realization platform to generate the machine code. Although the motor shaft consists of several disks which operate as different kinds of transducers, we used the slotted-opto transducer for shaft speed, and the tachogenerator, for producing the voltage proportional to the shaft speed [27]–[29].

2.3. Identification of the System

In order to determine the characteristic properties of the system under different conditions, the process reaction curve method is employed. A number of dynamical properties of the system such as rise time, settling time, and time constant can be obtained directly [24]. The armature of the DC motor is excited by a step input $u(t)$, of magnitude 4.5 Volts, and shaft speed is obtained in revolution per minute (RPM). The output voltage produced by the tachogenerator is measured to be 3.88 Volts that corresponds approximately to 1000 RPM shaft speed. Then, a second-order system model was approximated [24], [25].

$$G(s) \cong \frac{K}{(1+T_d s)(1+Ts)} = \frac{c}{s^2 + as + b} \qquad (5)$$

where the plant coefficients are calculated from the system output to be K=0.822, T_d=0.009 and T=0.1418s. Then the nominal model parameters are obtained as a=118.1663, b=783.5762, c=663.4948. [27].

$$\ddot{y}_m(t) = -a_n \dot{y}_m(t) - b_n y_m(t) + c_n u(t) + d(t) \qquad (6)$$

For more discussion about modelling and system identification issues interested readers are referred to [24], [27]–[31].

3. Application of the Controller

Various modifications of PID control scheme have been addressed in order to improve the closed-loop control performance [33], [34]. Since, control performance can decrease in the presence of noisy measurement during the experimental application. Further, the tuning of derivative term, which may amplify the high-frequency measurement noise, is another challenging task. In fact, as indicated in [32], the above arguments advise approximating the derivative term in most applications. Further, a PI-PD control [35], which is one of the modified forms with four parameter controller, can provide better control performance especially for controlling integrating, unstable as well as resonant processes while the classical PID control scheme may show poor performance [35]–[39]. In that control scheme, the transfer function of the PI controller affects both its poles and zeros, while, the PD controller affects only the poles. For further discussion about PI-PD controller the interested readers are referred to [37], [40], [41].

3.1. Modified Control Structure

The proposed control which is depicted in Fig. 4, wherein a proportional gain and a delay term are located in the inner loop for stabilizing the system and proportional integral controller is located in a forward path to reduce the steady-state error.

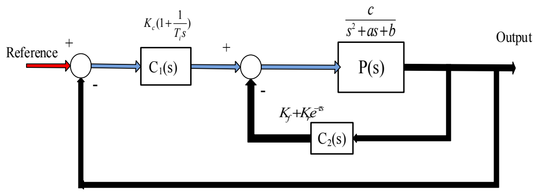

Fig. 4. PI-PR control scheme

The controller, which is given in Fig. 4, can be presented as follows.

$$C_{PI}(s) = K_P + \frac{K_i}{s} \tag{7}$$

$$C_{PR}(s) = K_f + K_R e^{-sh} \tag{8}$$

where $h>0$ is the delay and K_p, K_i, K_f, K_r represent controller parameters. Thus, $C_1(s)$ and $C_2(s)$ present the conventional PI and PR controllers, respectively. The closed-loop system can be presented as:

$$\frac{G(s)C_{PI}(s)}{1+G(s)(C_{PR}(s)+C_{PI}(s))} \tag{9}$$

Accordingly, the following transfer function is obtained.

$$\frac{\dfrac{K_p s+K_i}{s}\,\dfrac{c}{(s^2+as+b)}}{1+\left(\dfrac{c}{s^2+as+b}\right)\left(\dfrac{K_f s+K_R s e^{-sh}+K_p s+K_i}{s}\right)} \tag{10}$$

Then the characteristic equation can be written as

$$s^3+as^2+bs+cKps+cK_f s+cK_i+K_R c s e^{-sh} \tag{11}$$

As stated previously, the proposed control strategy is a variation of the one addressed in [10], however, a modified delayed output feedback controller is integrated. Considering the facts mentioned above, the characteristic equation of the system can be given as:

$$\Delta(s)=s^3+as^2+bs+cKps+cK_f s+cK_i+K_R c s e^{-sh} \tag{12}$$

which is a quasi-polynomial with the model parameters a, b, c are defined in Section 2. The closed-loop stability of the control system strictly depends on the location of the roots of the characteristic equation. It should be noted that the delay-free ($h=0$) system is stable under the following conditions:

$$a+K_f c+K_p c+K_R c>0,\quad K_i c>0 \tag{13}$$

Due to the limited space, we present only the sketch of the stability analysis of this type of control techniques. To mention a few, the stability regions are investigated with respect to delay (h) and the proportional gain of delay (k_r). A useful outline can be found in [42]. Accordingly, the computation of the roots of characteristic quasi-polynomial containing an infinite number of roots is a tedious task. Concerning to this matter, a number of algorithms have developed for the computation of the roots [43], [44]. It should be pointed out that the analytical tuning of the proposed controller is more difficult than the controller presented in [10]. However, we address an alternative and easy parameter tuning method to eliminate the aforementioned challenges.

3.2. Parameter Tuning

The inner control loop is designed based on the proportional delayed control strategy which is presented in [9]. The central notion is to place a triple real dominant root for the closed-loop system [9]. It is achieved by using a spectral analysis, which provides us more specific information about the dominant poles. According to this, the controller parameters are obtained by the following equations.

$$K_f=\frac{\left[(\sigma-\delta v)^2-v^2(1-\delta^2)\right]}{b} \tag{14}$$

$$h=\frac{1}{[\sigma-\delta v]} \tag{15}$$

$$K_r=\frac{\left[2(\sigma-\delta v)^2\right]}{be^{\sigma h}} \tag{16}$$

Then, the outer loop is tuned by the integral absolute error, which is a well-known minimization technique for controller parameter tuning.

$$J=\int |e(t)|\mathrm{d}t \tag{17}$$

By considering the results presented above, the controller's gains are chosen as in Table 2.

Table 2. Control parameters for PI-PR controller

	Controller Parameters					
	K_p	K_i	K_r	K_f	h	σ
PI-PR	2.84	82.32	0.00518	16.32	1.9231	59.376
PI-PD	K_p	K_i	K_d	K_{p2}		
	7.86	25.56	1.826	8.234		
PID	K_p	K_i	K_d			
	6.26	3.569	1.572			

4. Simulation and Experimental Results

The closed-loop control performance the elaborated control scheme are investigated experimentally. Furthermore, a comparison with conventional feedback controllers is performed to highlight the advantages of the elaborated control method.

The controller gains K_p, K_i and K_d are determined by classical controller design approaches based on a nominal system model obtained around a desired operating point. Figure 5 illustrates the set point response and the produced control signals are shown in Fig.6.

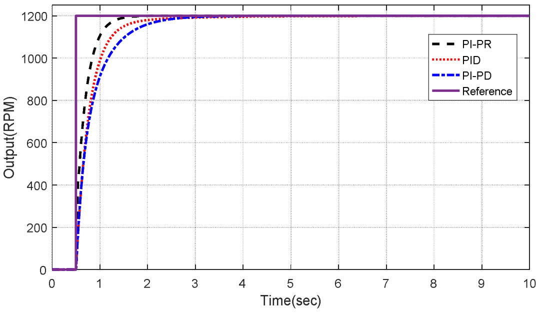

Fig. 5. Tracking performance of the controller

The main advantage of inserting a delay in the controller is that the closed-loop control system does not need any additional filter to attenuate noisy measurements. From the results, it can be concluded that PI-PR controller performs better results according to the quality of the control input.

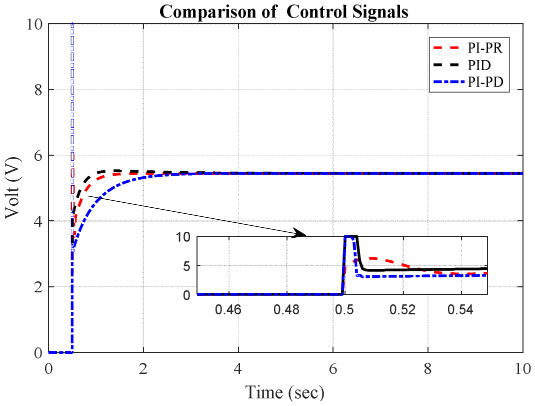

Fig. 6. Control signals

Further advantages can be summarized as follows. The PI-PR control scheme performs better transient response and tracking ability. It also produces a smooth control signal in the presence of noise. The performance comparison is presented in Table 3. and Table 4.

Table 3. Comparison of control performances

	PI-PR	PI-PD	PID
IAE	1.0332	1.8563	1.9856
EV	0.235	0.5313	0.3617
ISE	1.12	2.02	1.58

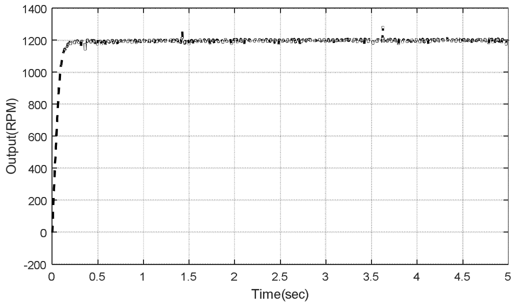

Fig. 7. Real-Time tracking performance of the controller

Table 4. Comparison of control signals

	PI-PR	PI-PD	PID
TV	0.1802	4.3625	0.3211
ISCI	82.1	122.78	93.12

The real-time experimental result is presented in Fig.7 and control signal is given in Fig. 8. From the realization point of view, a delay-based controller is more advantageous since it requires only memory registers which make it easier to implement. From another aspect, it would not be noise amplification problem since the controller does not contain any derivative term. Thus, it is not necessary to consider any additional filter during the experimental realization [9], [17].

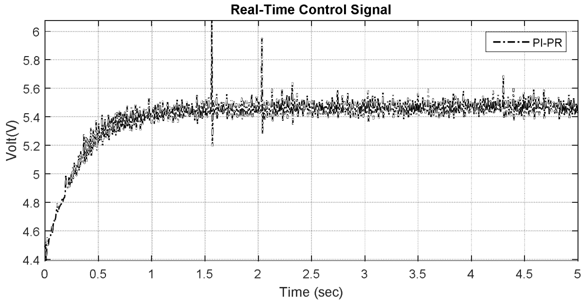

Fig. 8. Control signal of modified delay-based controller

However, it should be emphasized that the decay rate has to be determined carefully according to the actuator and experimentation limits such as sampling, quantization [9], [10].

5. Conclusion and Future Works

The controller shows satisfactory performance in terms of several performance metrics. This control scheme can be easily implemented for practical applications. Some advantages of the proposed control scheme are the better transient response, the fast convergence of tracking error, the smooth control signal as well as chattering attenuation. Yet another advantage of this controller is that it requires only memory registers which make it easier to implement. Furthermore, the designer does not need to use any estimation of the derivatives, which is a tedious task for the systems subject to measurement noise, delay, and uncertainties. As a result of that, the computational complexity of the problem, and the cost of the controller design will significantly reduce.

Future works will mainly focus on analytical controller parameter tuning. Stability regions will be depicted according to the delay and controller parameters changes. Further, disturbance rejection capability and robustness issues will be investigated.

6. Acknowledgment

The authors would like to thank the anonymous reviewers for careful reading of the manuscript and for their valuable comments. The work of N. Sinan Özbek is financially supported by TUBITAK under the 2214-A program. This work is financially supported by the scientific research department of Çukurova University under the FDK-5088 project number.

7. References

[1] W. Michiels and S.-I. Niculescu, *Stability, Control, and Computation for Time-Delay Systems*. Philadelphia, PA: Society for Industrial and

Applied Mathematics, 2014.

[2] R. Sipahi, T. Vyhlídal, S.-I. Niculescu, and Pierdomenico Pepe, *Time Delay Systems: Methods, Applications and New Trends*, vol. 423. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012.

[3] R. Sipahi, S.-I. Niculescu, C. T. Abdallah, W. Michiels, and Keqin Gu, “Stability and Stabilization of Systems with Time Delay,” *IEEE Control Syst.*, vol. 31, no. 1, pp. 38–65, Feb. 2011.

[4] I. Suh and Z. Bien, “Proportional minus delay controller,” *IEEE Trans. Automat. Contr.*, vol. 24, no. 2, pp. 370–372, Apr. 1979.

[5] H. Suh and Z. Bien, “Use of time-delay actions in the controller design,” *IEEE Trans. Automat. Contr.*, vol. 25, no. 3, pp. 600–603, Jun. 1980.

[6] K. Youcef-Toumi and O. Ito, “A Time Delay Controller for Systems With Unknown Dynamics,” *J. Dyn. Syst. Meas. Control*, vol. 112, no. 1, p. 133, 1990.

[7] C. Abdallah, P. Dorato, J. Benites-Read, and R. Byrne, “Delayed Positive Feedback Can Stabilize Oscillatory Systems,” *1993 Am. Control Conf.*, vol. 2, no. 12, pp. 3106–3107, 1993.

[8] H. Kokame, K. Hirata, K. Konishi, and T. Mori, “Difference feedback can stabilize uncertain steady states,” *IEEE Trans. Automat. Contr.*, vol. 46, no. 12, pp. 1908–1913, 2001.

[9] R. Villafuerte, S. Mondie, and R. Garrido, “Tuning of Proportional Retarded Controllers: Theory and Experiments,” *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 3, pp. 983–990, May 2013.

[10] A. Ramirez, S. Mondie, R. Garrido, and R. Sipahi, “Design of Proportional-Integral-Retarded (PIR) Controllers for Second-Order LTI Systems,” *IEEE Trans. Automat. Contr.*, vol. 61, no. 6, pp. 1688–1693, Jun. 2016.

[11] A. Ramírez, S. Mondié, and R. Garrido, “Proportional Integral Retarded Control of Second Order Linear Systems,” no. 1, pp. 2239–2244, 2013.

[12] W. Kwon and A. Pearson, “Feedback stabilization of linear systems with delayed control,” *IEEE Trans. Automat. Contr.*, vol. 25, no. 2, pp. 266–269, Apr. 1980.

[13] W. H. Kwon, G. Won, and W. Kim, “Delayed State Feedback Controller for the Stabilization of Ordinary Systems,” in *American Control Conference*, 1989, vol. 3, pp. 292–297.

[14] U. Zalluhoglu, A. S. Kammer, and N. Olgac, “Delayed Feedback Control Laws for Rijke Tube Thermoacoustic Instability, Synthesis, and Experimental Validation,” *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 5, pp. 1861–1868, Sep. 2016.

[15] A. Galip Ulsoy, “Time-Delayed Control of SISO Systems for Improved Stability Margins,” *J. Dyn. Syst. Meas. Control*, vol. 137, no. 4, p. 41014, Apr. 2015.

[16] A. Ramírez, R. Garrido, and S. Mondié, “Velocity control of servo systems using an integral retarded algorithm,” *ISA Trans.*, vol. 58, pp. 357–366, Sep. 2015.

[17] A. Ramírez, R. Sipahi, S. Mondié, and R. Garrido, “Design of Maximum Decay Rate for SISO Systems with Delayed Output Feedback Using Elimination Theory∗∗This work has been supported by CONACYT grant 180725 and PNPC, and developed in part during A. Ramírez’s visit to R. Sipahi at Northeastern University.,” *IFAC-PapersOnLine*, vol. 48, no. 12, pp. 221–226, 2015.

[18] J. Lee and T. F. Edgar, “Improved PI Controller with Delayed or Filtered Integral Mode,” vol. 48, no. 12, 2002.

[19] Q.-C. Zhong, “A Delay-type PID Controller,” in *IFAC 2002, IFAC World Congres*, 2002, pp. 4–9.

[20] A. Ramirez, R. Sipahi, S. Mondie, and R. Garrido, “An Analytical Approach to Tuning of Delay-Based Controllers for LTI-SISO Systems,” *SIAM J. Control Optim.*, vol. 55, no. 1, pp. 397–412, Jan. 2017.

[21] N. S. Ozbek and I. Eker, “Investigation of time-delayed controller design strategies for an electromechanical system,” in *2017 4th International Conference on Electrical and Electronic Engineering (ICEEE)*, 2017, pp. 181–186.

[22] K. López, R. Garrido, and S. Mondié, “Position control of servodrives using a Cascade Proportional Integral Retarded controller,” in *2017 International Conference on Control, Decision and Information Technologies (CoDIT)*, 2017, pp. 1–5.

[23] J.-E. Hernández-Díez, C.-F. Méndez-Barrios, S. Mondié, S.-I. Niculescu, and E. J. González-Galván, “Proportional-delayed controllers design for LTI-systems: a geometric approach,” *Int. J. Control*, vol. 7179, no. April, pp. 1–19, Mar. 2017.

[24] İ. Eker, “Experimental on-line identification of an electromechanical system,” *ISA Trans.*, vol. 43, no. 1, pp. 13–22, Jan. 2004.

[25] M. Furat and İ. Eker, “Second-order integral sliding-mode control with experimental application,” *ISA Trans.*, vol. 53, no. 5, pp. 1661–1669, Sep. 2014.

[26] İ. Eker, “Sliding mode control with PID sliding surface and experimental application to an electromechanical plant,” *ISA Trans.*, vol. 45, no. 1, pp. 109–118, Jan. 2006.

[27] M. FURAT and İ. EKER, “Chattering-eliminated adaptive sliding-mode control: an experimental comparison study,” *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 24, pp. 605–620, 2016.

[28] M. Furat and İ. Eker, “Experimental Evaluation of Sliding-Mode Control Techniques Kaymalı - Kutup Kontrol Tekniklerinin Deneysel Değerlendirilmesi,” vol. 27, no. June, pp. 23–37, 2012.

[29] N. S. Ozbek and I. Eker, “A novel interactive system identification and control toolbox dedicated to real-time identification and model reference adaptive control experiments,” in *2015 9th International Conference on Electrical and Electronics Engineering (ELECO)*, 2015, pp. 859–863.

[30] M. Furat and İ. Eker, “Computer-aided experimental modeling of a real system using graphical analysis of a step response data,” *Comput. Appl. Eng. Educ.*, vol. 22, no. 4, pp. 571–582, Dec. 2014.

[31] N. S. Özbek and İ. Eker, “An interactive computer-aided instructional strategy and assessment methods for system identification and adaptive control laboratory,” *IEEE Trans. Educ.*, vol. 58, no. 4, pp. 297–302, 2015.

[32] V. R. Segovia, T. Hägglund, and K. J. Åström, “Measurement noise filtering for common PID tuning rules,” *Control Eng. Pract.*, vol. 32, pp. 43–63, Nov. 2014.

[33] M. A. Johnson and M. H. Moradi, *PID Control*. London: Springer-Verlag, 2005.

[34] K. Astrom and B. Wittemmark, *Computer-Controlled Systems: Theory and Design*, 3rd editio. Englewood Cliffs, NJ: Prentice-Hall, 1997.

[35] D. Atherton, “PI-PD, an Extension of Proportional–Integral–Derivative Control,” *Meas. Control*, vol. 49, no. 5, pp. 161–165, Jun. 2016.

[36] N. Tan, “Computation of stabilizing PI-PD controllers,” *Int. J. Control. Autom. Syst.*, vol. 7, no. 2, pp. 175–184, Apr. 2009.

[37] I. Kaya, “PI-PD controllers for controlling stable processes with inverse response and dead time,” *Electr. Eng.*, vol. 98, no. 1, pp. 55–65, Mar. 2016.

[38] I. Kaya and D. P. Atherton, “A PI-PD controller design for integrat- ing processes,” in *American Control Conference*, 1999, pp. 258–262.

[39] D. P. Atherton and S. Majhi, “Limitations of PID controllers,” in *Proceedings of the 1999 American Control Conference (Cat. No. 99CH36251)*, 1999, vol. 6, no. June, pp. 3843–3847 vol.6.

[40] D. P. Atherton and A. F. Boz, “Using standard forms for controller design,” in *UKACC International Conference on Control (CONTROL ’98)*, 1998, vol. 1998, pp. 1066–1071.

[41] İ. Kaya, N. Tan, and D. P. Atherton, “Improved cascade control structure for enhanced performance,” *J. Process Control*, vol. 17, no. 1, pp. 3–16, Jan. 2007.

[42] R. Datko, “A procedure for determination of the exponential stability of certain differential-difference equations,” *Q. Appl. Math.*, vol. 36, no. 3, pp. 279–292, Oct. 1978.

[43] P. Zítek, J. Fišer, and T. Vyhlídal, “Dimensional analysis approach to dominant three-pole placement in delayed PID control loops,” *J. Process Control*, vol. 23, no. 8, pp. 1063–1074, Sep. 2013.

[44] T. Vyhlidal and P. Zitek, “Mapping Based Algorithm for Large-Scale Computation of Quasi-Polynomial Zeros,” *IEEE Trans. Automat. Contr.*, vol. 54, no. 1, pp. 171–177, Jan. 2009.