ppi 201502ZU4659
Esta publicación científica en formato digital es
continuidad de la revista impresa
ISSN 0254-0770 / Depósito legal pp 197802ZU38

Hacia los 130 años de creación de la Universidad del Zulia

"Buscar la verdad y afianzar los valores transcendentales", misión de las universidades en su artículo primero, inspirado en los principios humanísticos. Ley de Universidades 8 de septiembre de 1970.

REVISTA TÉCNICA
DE LA FACULTAD DE INGENIERÍA

Una Revista Internacional Arbitrada que está indizada en las publicaciones de referencia y comentarios:

- SCOPUS
- Compendex
- Chemical Abstracts
- Metal Abstracts
- World Aluminium Abstracts
- Mathematical Reviews
- Petroleum Abstracts
- Current Mathematical Publications
- MathSci
- Revencyt
- Materials Information
- Periódica
- Actualidad Iberoamericana

REVISTA TÉCNICA
DE LA FACULTAD DE INGENIERÍA

UNIVERSIDAD DEL ZULIA

VOLUME 43 SEPTEMBER - DECEMBER 2020 NUMBER 3

Design and construction of an analogue control module lead-lag type as a learning tool in control theory

*Jormany Quintero-Rojas[1]**, *Cecilia Bermúdez[1]*, *María Coronel[2]*

[1]Departamento de Sistemas de Control, Escuela Ingeniería de Sistemas, Facultad de Ingeniería, Universidad de Los Andes, Apartado 5101, Mérida, Venezuela.
[2]Escuela de Ingeniería Eléctrica, Facultad de Ingeniería, Universidad de Los Andes, Apartado 5101, Mérida, Venezuela.
*Autor de correspondencia: jormany@ula.ve
https://doi.org/10.22209/rt.v43n3a05
Received: 09/10/2019 **|** Accepted: 06/07/2020 **|** Available:: 01/09/2020

Abstract

Lead-lag compensators are still used for the control of various real systems, therefore, they are an indispensable topic in the study of automatic process control. In the teaching of control theory, the need for didactic systems is evident to offer the possibility of experimenting with analog controllers, this way the theoretical knowledge is strengthened with practice. The object of this work is to describe the design and implementation of a control module based on lead-lag controllers as a physical tool in teaching the theoretical principles of automatic control. The control module was built with easy use and low cost elements in Venezuela. This module features four independent sub-modules: two controllers and two electrical systems to be controlled, which can be connected to each other. The results obtained with the control module slightly differ from the simulations. This designed module allows the user to develop analysis skills in control systems by single, friendly and safe interaction when varying controller parameters.

Keywords: control systems; control teaching module; lead-lag controller; analogue control.

Diseño y construcción de un módulo de control analógico tipo adelanto-atraso como herramienta de aprendizaje en la teoría de control

Resumen

Los compensadores de adelanto y atraso aún son utilizados para el control de diversos sistemas reales, por lo cual es un tema indispensable en las cátedras de control automático de procesos. En la enseñanza de la teoría de control es cada vez más necesario contar con sistemas didácticos que ofrezcan la posibilidad de fortalecer los conocimientos teóricos con la práctica. El presente trabajo tiene por objetivo describir el diseño e implementación de un módulo de control basado en controladores de tipo adelanto-atraso como herramienta física en la enseñanza los principios teóricos del control automático. El módulo de control fue construido con elementos de fácil uso y bajo costo en Venezuela. Este presenta cuatro sub-módulos independientes: dos controladores y dos sistemas eléctricos a controlar, que pueden conectarse entre si. Los resultados obtenidos con el módulo de control difieren muy poco de las simulaciones. Este módulo diseñado permite al usuario desarrollar habilidades de análisis en los sistemas de control por la interacción amigable, sencilla y segura al momento de variar los parámetros del controlador.

Palabras clave: sistemas de control; módulo didáctico de control; controlador adelanto-atraso; control analógico.

Introduction

Control theory involves the study of a set of strategies or laws that allow processes to be regulated in the desired way. These laws include PID and Sliding Mode Control [1], anti-windup compensation [2], in addition to other classic control laws. For this purpose, a device that allows regulating variables under these control lawsis needed, device known as the controller. An analog controller is a system that implements a control law, which is made up of a set of basic electronic elements such as resistors, capacitors, and integrated circuits. There are different types of analog control laws, such as PID, full state feedback, lead-lag compensators, among others [3].

Lead-lag compensators allow reference tracking, in addition to improving the response of the controlled system. The lag compensation manages to increase the closed-loop gain, which allows improving the steady-state errorwithout modifying the transient state of the system; while the lead compensation creates a phase lead in the system adjusting the response of the transient state to the required behavior specifications [4-6]. Lead-lag controllers are one of the frequently used analog controllers, designed to improve steady-state and the transient state of the system to be controlled. Among its uses are the control of double rotor systems to overcome deficiencies in PID controllers [7], control of the sliding speed in three-machine systems [8], control of the fractional-order system using Matsuda's fourth-order integer approximation [9], in addition to others.

Technological advances in the teaching of control theory exhort today's student to master theory and practice [10-12]; however, it is difficult to have the equipment and physical components to develop such practices. For this reason, the practice activities are being replaced by simulations for the study and interaction of control systems [6,11,13-15]. Therefore, the control engineering teaching process needs to have physical didactic platforms that allow experimentation with variations in the parameters of an analog controller [12,16]. Currently, there are several proposals for academic and commercial didactic modules in the study of control theory. Particularly some modules implement the PID control [16-20] and academic modules with controllers that use components and equipment that are difficult to access [10,20-23]. Among the commercial options that use lead-lag compensators, high-cost laboratory equipment stands out, this presents a disadvantage for the acquisition

[13]. Therefore, it is desiderable to have equipment for similar purposes, but at a low cost. For the aforementioned, the purpose of this work is to describe the design and implementation of a control module based on the lead-lag compensator as a physical tool in teaching the theoretical principles of automatic control.

Experimental

LCBox control module design

The control module design (Lead-Lag Control Box, LCBox) is a simple and efficient design based on the classic closed-loop system scheme. It consists of two blocks, the first one has the electronic controllers (lead or lag and lead-lag) and the second block contains two linear electronic systems, one second-order and another third order. Both controllers and systems, allow the exchange of physical parameters, capacitors or resistors, through connectors.

The block diagram configuration of the different submodules that constitute the LCBox is illustrated in Figure 1. The dotted lines represent interchangeable connections. The lines to the left of the systems represent the control signals of the different controllers and the line to the right represents the connection to the out point.

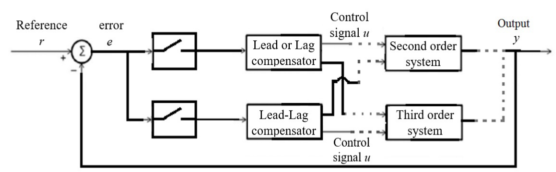

Figure 1. Block diagram of the LCBox control module.

As it is a closed-loop control system, it is necessary to incorporate a unitary subtraction element implemented with an operational amplifier in its differential configuration,according to Figure 2. A +12V and another –12V Power sources were selected to adjust the allowed voltage range supply for operational amplifiers.

For the choice of linear systems, a second-order system and another third-order system were used. The selected second-order system is shown in Figure 3. The mathematical model that describes the dynamics of this system is given by equation1 and equation 2:

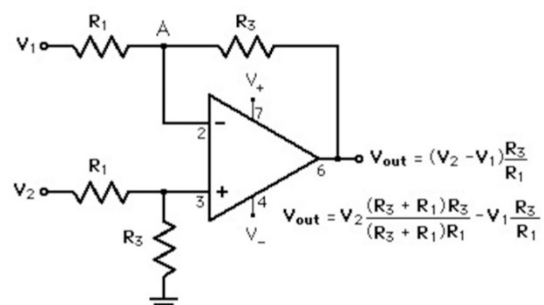

Figure 2. Differentialamplifierconfiguration

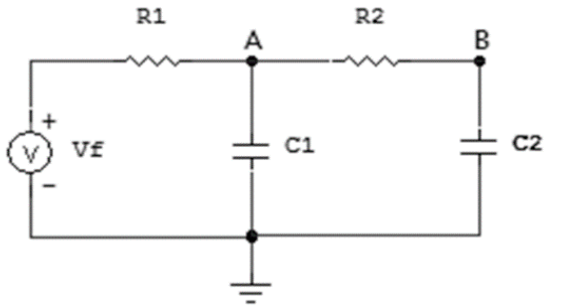

Figure 3. Second-ordercircuit

$$x = \begin{bmatrix} VC1 \\ VC2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (1)$$

$$\dot{x} = \begin{bmatrix} \frac{-1}{C_1R_1} - \frac{1}{C_1R_2} & \frac{1}{C_1R_2} \\ \frac{1}{C_2R_2} & -\frac{1}{C_2R_2} \end{bmatrix} x + \begin{bmatrix} \frac{1}{C_1R_1} \\ 0 \end{bmatrix} u \quad (2)$$

$$y = [0 \quad 1]x$$

The voltage in the capacitor C2 (VC2) was defined as a controlled variable, to avoid the appearance of finite zeros in the transfer function. The appearance of zero can significantly influence closed-loop control, interfering with the output of the system. The transfer function for this case corresponds to equation 3.

$$G(s) = \frac{1}{R_1R_2C_1C_2s^2+(R_1C_1+R_1C_2+R_2C_2)s+1} \quad (3)$$

The selected third-order system is shown in Figure 4. Equations 4 and 5 describe the mathematical model in the system state space.

$$x = \begin{bmatrix} VC_1 \\ VC_2 \\ VC_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (4)$$

In this case, the output is defined as the voltage at capacitor C3 (VC3), for the reasons explained in the case of the second-order system.

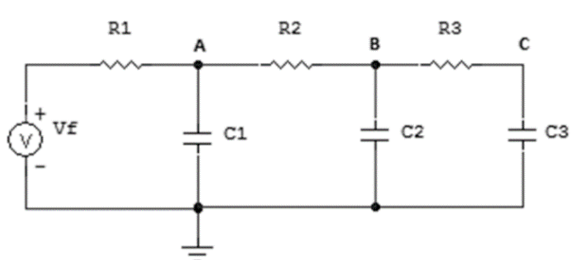

Figure 4. Third-ordercircuit.

$$\dot{x} = \begin{bmatrix} -\frac{1}{C_1R_1} - \frac{1}{C_1R_2} & \frac{1}{C_1R_2} & 0 \\ \frac{1}{C_2R_2} & -\frac{1}{C_2R_3} - \frac{1}{C_2R_2} & -\frac{1}{C_2R_3} \\ 0 & \frac{1}{C_3R_3} & -\frac{1}{C_3R_3} \end{bmatrix} x + \begin{bmatrix} \frac{1}{C_1R_1} \\ 0 \\ 0 \end{bmatrix} u \quad (5)$$

$$y = [0 \quad 0 \quad 1]x$$

Considering equation 5, the equivalent transfer function is described in equation 6

$$G(s) = \frac{1}{as^3+bs^2+cs+1} \quad (6)$$

Where the parameters of the polynomial are described in equation 7.

$$\begin{aligned} a &= R_1R_2R_3C_1C_2C_3 \\ b &= R_1R_2C_1C_2 + R_1R_2C_1C_3 + R_1R_3C_1C_3 + R_1R_3C_2C_3 + R_2R_3C_2C_3 \quad (7) \\ c &= R_1C_1 + R_1C_2 + R_1C_3 + R_2C_2 + R_2C_3 + R_3C_3 \end{aligned}$$

Lead or lag controller design

This design includes two operational amplifiers as illustrated in Figure 5. The transfer function of the circuit is given by equation 8.

$$G_c(s) = \frac{E_o(s)}{E_i(s)} = \frac{R_4R_2}{R_1R_3}\frac{R_1C_1s+1}{R_2C_2s+1} = K_c\frac{s+1/T}{s+1/T\alpha} \quad (8)$$

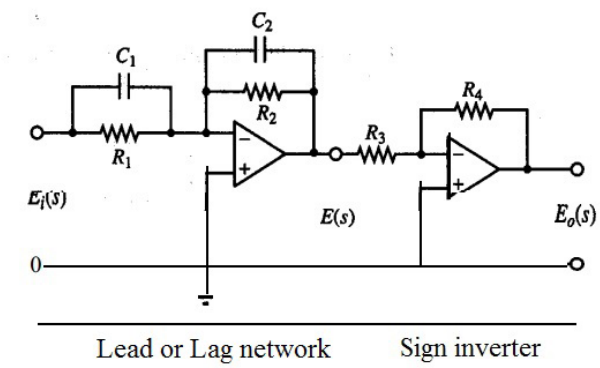

Figure 5. Schematic design of a lead or lag compensator with operational amplifiers.

The relationship betweenthe controller parameters to the physical components is described in equation 9.

$$T = R_1C_1; \ \alpha = \frac{R_2C_2}{R_1C_1}; \ K_c = \frac{R_4C_1}{R_3C_2} \quad (9)$$

To reduce the number of parameters, C = C1 = C2. So equation 8 is rewritten as equation 10.

$$G_c(s)=\frac{E_o(s)}{E_i(s)}=\frac{R_4R_2}{R_1R_3}\frac{R_1Cs+1}{R_2Cs+1}=K_c\frac{s+1/T}{s+1/T\alpha} \quad (10)$$

The equivalence between the controller parameters and the physical components are given by equation 11.

$$T=R_1C;\ \alpha=\frac{R_2}{R_1};\ K_c=\frac{R_4}{R_3} \quad (11)$$

The transfer function, equation 10, represents a phase lag controller, provided that α> 1 is satisfied, or phase lead if the inequality 0 <α<1 is satisfied[24].

Lead-lag controller design

This controller combines both networks (lead and lag) into a single control element. The design of the compensators is carried out separately, equation 12 represents the classic transfer function for the aforementioned.

$$G_c(s)=G_{c1}(s)G_{c2}(s)=K_c\alpha_1\frac{1+T_1s}{1+\alpha_1T_1s}\alpha_2\frac{1+T_2s}{1+\alpha_2T_2s} \quad (12)$$

The inequalities 0 <α1 <1 and α2> 1 must be met, for this the adjustment of the lead network and then the lag network is carried out. Figure 6 representsthe equivalent circuit to the transfer function described in equation 13.

$$G_c(s)=\frac{R_6R_4}{R_5R_3}\frac{1+(R_1+R_3)C_1s}{1+R_1C_1s}\frac{1+R_2C_2s}{1+(R_2+R_4)C_2s} \quad (13)$$

The relation between the parameters and physical components is given by equation 14.

$$T_1=(R_1+R_3)C_1;\ T_2=R_2C_2;\ \alpha_1=\frac{R_1}{R_1+R_3};\ \alpha_2=\frac{R_2+R_4}{R_2};\ K_c=\frac{R_6R_4R_1}{R_5R_3R_2}\frac{R_1+R_3}{R_4+R_2} \quad (14)$$

It should be verified that 0 <α_1 <1 and α_2> 1 [24].

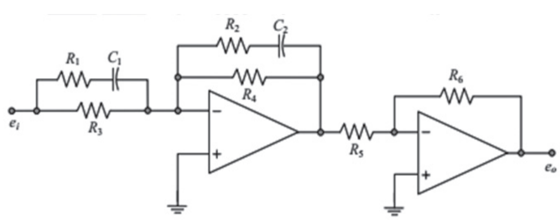

Figure 6. Lead-lag controller circuit.

Selection of components for implementation

The used elements show easy use, adquisition and low cost in Venezuela as characteristics. The LM741 operational amplifier froma well established supplieris used in several analog applications related to control. It was chosen for its wide gain andvaried operating voltage ranges, allowing it to achieve exceptional performance as an integrator and summing amplifier [25]. The configuration of the compensators could be made with other more economic integrated circuits, however, forthis investigation sakeand availability of acquisition, the integrated LM741 was choosen.

Four carbon film resistors from 1KΩ were used in the implementation of the control loop subtractor, to ensure the unit gain of the control loop. The user selects the desired controller employing a dip switch. A (150x90) mm copper faced bakelite board was used for circuit printing. The connections between the controllers, the systems, and the interchangeable electronic components are made using header bases. Banana plugs were used for the input, ground, +12V, and -12V connections of the LCBox, and the output of the control module. Connectors were fixed on the board, to carry out the exchange of some components in case of failure.

Input protection

The system reference input and the power inputs of the operational amplifiers +12V and-12V are protected. A 0.1A fuse is included for overload or short circuit protection, the acceptable nominal current range is 0.1A, 0.25A or 0.5A. The +12V and -12V supply of the LCBox are protected using two voltage regulators: An LM7812 for the +12V input and an LM7912 for the -12V input. Figures 7 and 8 illustrate the configurations used. Table 1 summarizes the components used to make the LCBox control module and their prices in US dollars.

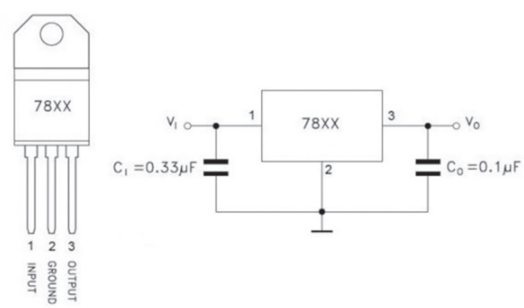

Figure 7. Application of the LM7812 Voltage Regulator.

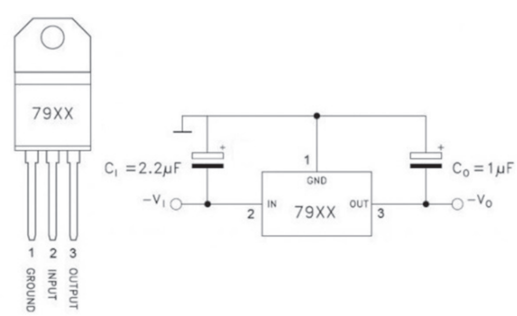

Figure 8. Application of the LM7912 Voltage Regulator.

Table 1. Components used in the implementation of the LCBox control module

Schematic symbol	Value	Componentdescription	Quantity	Unitprice (USD)
U1, U2, U3, U4, U5, U6, U7, U8	---	OperationalAmplifier	8	0.99
R1, R3, R4, R5	1000Ω	Resistor	4	0.004
C10, C11	0.33µF y 0.1µF	Electrolytic capacitor	2	0.0193
C12, C13	2.2µF y 1µF	Tantalum capacitor	2	0.0398
---	---	Bakelite PCB (10x15)cm	1	2.28
---	---	6PIN Headersconnector	14	0.0955
---	---	Male Banana Plugs	5	0.1995
---	---	DIP-8 IC DIP Sockets	8	0.138
---	0.1 A	European Fuse	1	0.498
---	---	European Fuse Holder	1	0.663
---	12V	VoltageRegulator LM7812	1	0.127
---	-12V	VoltageRegulator LM7912	1	0.246
Total cost				**15.307**

LCBox control module construction

The schematic design of the LCBox control module made in the ISIS software is illustrated in Figure 9. Once the design was made, the ARES software was used to create the tracks or connections between the components of the printed circuit, as shown in Figure 10. For the printed circuit, the bakelite printing technique was used, the result is shown in Figure 11. The upper part of the LCBox contains a user guide connection diagram, which is illustrated in Figure 12. The upper part of the LCBox has five terminals, four input terminals (reference, ground, 12V, -12V) and one output terminal (to display the system's output), as well as header connectors.

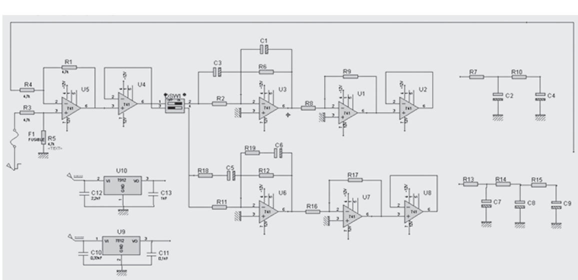

Figure 9. Schematic diagram obtained with Proteus' ISIS for the LCBox control module

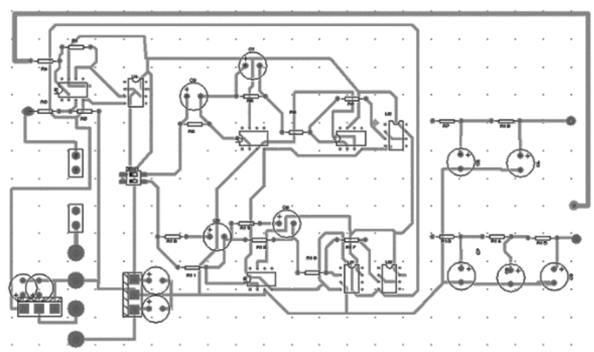

Figure 10. Design obtained in ARES by Proteus to make the printed circuit board (PCB) of the LCBox.

Figure 11. Upperside of the printed circuit board

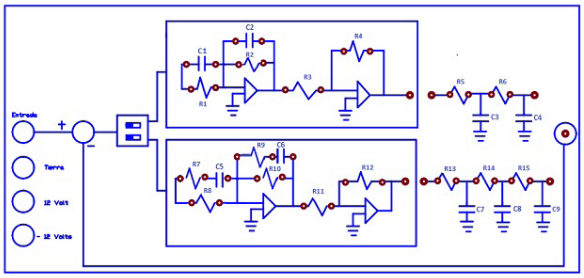

Figure 12. Top of the LCBox module

Unlike the upper part, the rest of the module is made of steel. Inside the module, insulating bases were built for the plate, which protects the components and lines against short circuits. The cover of the LCBox and the container were joined by a pair of hinges. The final result of the construction of the LCBox is shown in Figure 13.

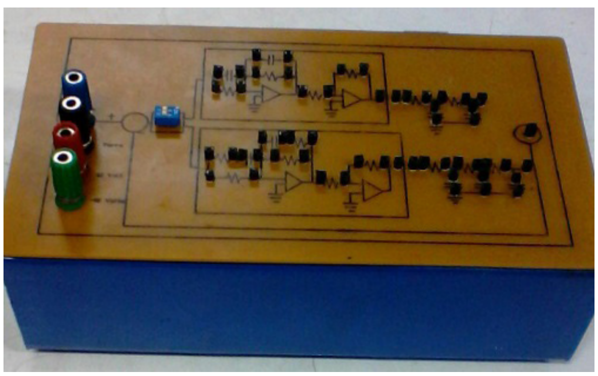

Figure 13. View of the lead-lag analog control module finished, LCBox

Operating range of the LCBox module

Table 2 and Figure 12 describe the operating limits and location of each component to be connected to the module. The maximum and minimum voltage that the reference input can withstand is given by the capacity of the operational amplifiers used. These values can be found in the datasheet of the LM741 package [25]. The minimum and maximum values of the capacitors and resistors represent the range of values with which the LCBox was successfully tested.

Table 2.Operating range of the LCBox control module.

Symbol onthecover	MinValue	MaxValue
Reference	-15V	15V
12 Volts	7.5V	35V
-12 Volts	-35V	-6.1V
C1, C2, C5, C6	0.1 µF	100 µF
R1, R2, R3, R4, R7, R8, R9, R10, R11, R12	39Ω	180KΩ

Results and Discussion

To check the performance of the control module, different tests were carried out. A square wave from a signal generator was used as a reference signal and the output signal of the controlled system was recorded in a closed loop with the help of an oscilloscope.

Lead compensation in the second-order system

For the system to be controlled, the following parameters were used: C3 = 1µF, C4 = 2.2µF, R5 = 1000Ω and R6 = 2000Ω, which provide over-damped dynamics. In this case, we set upthe closed-loop system to meet the following requirements: $error_p$ 6% (position error) and 10%<%SD<20% (variation of the oveshoot). Applying the desing algorithm in the lead controller, andthrough the frequency method the controller parameters K_c= 22.6659, α = 0.7059, and T = 5.7499x10^{-4} were obtained. The transfer function of the advance compensator (equation 8) is then turn into equation 15.

$$G_c(s) = \frac{22{,}67s+3{,}942.10^4}{s+2464} \quad (15)$$

The values for the implementation of the controller were calculated using equation 11 and the parameters used were: R_1 = 4721Ω ≈ 4700Ω, R_2 = 1029Ω ≈ 1000Ω, R_3 = 120Ω, R_4 = 12783.56Ω ≈ 13000Ω, C_1= 0.1µF y C_2 = 0.47 µF. The data of the real output of the closed-loop system was stored and compared with the simulations performed in the *PSIM* and *MATLAB* software, as shown in Figure 14. The curves were plotted in *MATLAB* for comparison. The output plots provide a very good approximation of the real data with the simulated data in the *PSIM* software. It can be seen how it reaches the desired maximum overshootand follows the reference within the established range, this behavior is due to the good choice of the controller parameters.

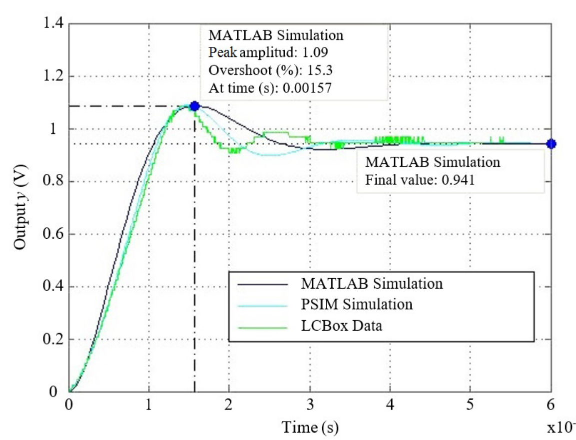

Figure 14.LCBox output signal for the closed-loop lead compensator

Lag compensator in the second-order system

For this case, the following parameters were used: C_3 = 0.1μF, C_4 = 0.22μF, R_5 = 1000Ω y R_6 = 2000Ω, with which an open-loop overdamping dynamics is obtained in a second order system. The system is to be built to meet the following control requirements: $error_p$< 3% and %SD = 0%. As in the previous case, the parameters for the delay controller K_c= 1.2136, α = 28.8403 and T = 0.022 were calculated and its transfer function is described in equation 16.

$$G_c(s) = \frac{1{,}214s+557}{s+15{,}92} \tag{16}$$

The following real parameters were calculated for the implementation of the controller: R_1 = 2047Ω ≈ 2000Ω, R_2 = 62101Ω ≈ 62000Ω, R_3 = 120Ω, R_4 = 1354Ω ≈ 1500Ω, C_1= 10μF y C_2 = 10μF. The response of the system is shown in Figure 15, it is seen how the real curve corresponds to the curve simulated by the *PSIM* software, complying with the value of the reference set and the simulated dynamics.

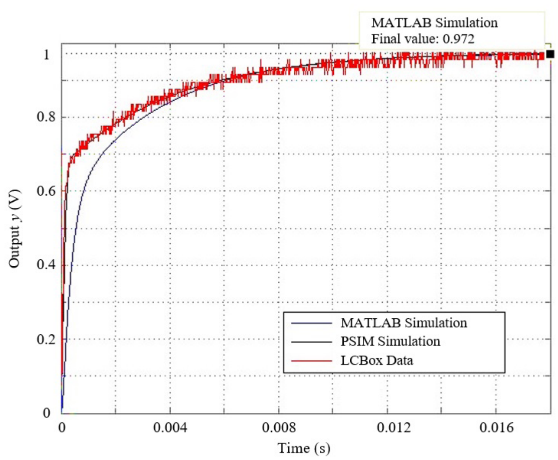

Figure 15. LCBox output curve for lag compensator.

Lead- Lag compensator in the third-order system

For this system, a lead-lag controller was used. The system parameters were as follows: C_7 = 0.1μF, C_8 = 0.22μF, C_9 = 0.33μF, R_{13} = 2000Ω, R_{14} = 1000Ω y R_{15} = 3000Ω, corresponding to a third-order system with overdamped dynamics.

The closed-loop system must comply with: errorp< 2% and %SD < 10%. The controller design algorithm was applied by lead-lag motion under the frequency method and the following parameters were obtained K_c= 48.07168, α_1 = 0.2169, α_2 = 5.7544, T_1 = 3.4633x10^{-4}, T_2 = 0.0028, the transfer function for the controller described in equation 17 was obtained.

$$G_c(s) = \frac{48{,}08s^2+3{,}106.10^4s+4{,}959.10^6}{s^2+1{,}393.10^3+8{,}264.10^4} \tag{17}$$

Taking into account the equivalencies of equation 14, the most suitable physical parameters for the controller were determined. The values used were: R_7 = 1500Ω ≈ 2000Ω, R_8 = 411.764Ω ≈ 410Ω, R_9 = 500Ω ≈ 510Ω, R_{10} = 1963.299Ω ≈ 1900Ω, R_{11} = 410Ω, R_{12} = 31291Ω ≈ 3000Ω, C_5= 0.10829 μF y C_6 = 6.8 μF. Figure 16 shows how the real output of the system controlled by the lead-lag compensator approaches with good accuracy the curve simulated in the *PSIM* and *MATLAB* software achieving the design specifications.

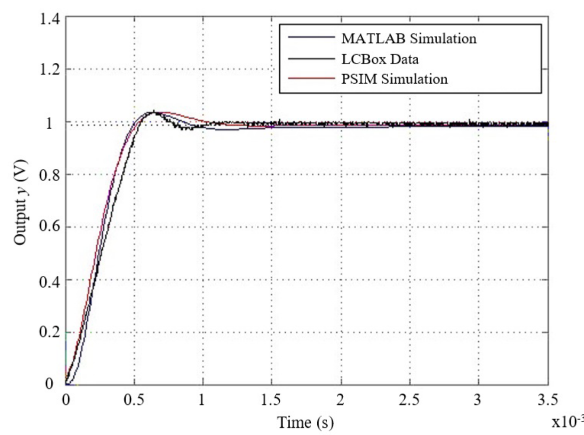

Figure 16.LCBox output curve for the lead-lag compensator

Conclusions

The LCBox is a platform of great potential designed to be used in the teaching of control theory, because of its simplicity in its construction, use, and handling. It allows the user to implement lead, lag, or lead-lag compensators designed in theory and set up with basic electronic elements to control electrical systems, thus avoiding errors in wiring and wrong configurations in the amplifiers. Being a simple design, it allows the user of different engineering specialties to develop analytical skills in the control systems by the friendly and safe interaction when changing the controller parameters.

It should be noted that the construction of the module was done with electronic elements and devices of easy acquisition and low cost, so it makes the LCBox a controller simple, powerful, robust, and easy construction. The control module only contains two types ofcontrollers, however, this presents a disadvantage for the study of other different analog control strategies.

References

[1] Baldeón, J., Escorza, J., Chávez, D., & Camacho, O.: “Control for hexacopters: A sliding mode control and PID comparison”. Rev. Téc. Ing. Univ. Zulia, Vol. 39, No. 3(2016), 137-144.

[2] Ríos-Bolívar, A.: “Controller synthesis with compensation AW and performance in H2/H∞”. Rev. Téc. Ing. Univ. Zulia., Vol. 30, No. 3 (2007), 263-272.

[3] Ogata, K.: “Ingeniería de control moderna”. Pearson Educación, S.A., Madrid, 2010.

[4] Kuo, B.: “Sistemas de control automático”. Prentice Hall, México, 1996.

[5] Hassaan, G.: “Robustness of feedback first-order lag-lead, feedforward second-order lag-lead and feedforward first-order lag-lead compensators used with second-order processes”. International Journal of Advances in Engineering&Technology, Vol. 7, No.6(2015), 1711.

[6] Martínez, J., Padilla, A., Rodríguez, E., Jiménez, A., & Orozco, H.: “Diseño de herramientas didácticas enfocadas al aprendizaje de sistemas de control utilizando instrumentación virtual”. Revista Iberoamericana de Automática e Informática industrial, Vol. 14, No. 4 (2017), 424-433.

[7] Deniz, M., Tatlicioglu, E., y Bayrak, A.: “Experimental Verification of Lead-Lag Compensators on a Twin Rotor System”. Electrical, Control and CommunicationEngineering, Vol. 14, No. 2 (2018), 164-171.

[8] Jalali, S., & Shahgholian, G.: “Designing of power system stabilizer based on the root locus method with lead-lag controller and comparing it with PI controller in multi-machine power system”. Journal of Power Technologies, Vol. 98, No. 1 (2018), 45-56.

[9] Dogruer, T., & Tan, N.: “Lead and lag controller design in fractional-order control systems”. Measurement and Control, (2019), doi:0020294019858094.

[10] Silva, L., Pereira, R., Gonzatti, R., da Silva, L., Lambert-Torres, G., Mollica, D., & Santana Filho, J.: Low-cost didactic module for single-phase inverter teaching. In: IEEE (ed), 2017 Brazilian Power Electronics Conference (COBEP),(2017).doi: 10.1109/COBEP.2017.8257232.

[11] Tapia, J., Rodas, A., & Camacho, O.: “Comparación de dos enfoques para la enseñanza en Control de Procesos: Simulación versus Implementación”. Revista Ibérica de Sistemas e Tecnologias de Informação, No.E23 (2019),206-219.

[12] Brito, M., Melo, F, Freitas, L., Vieira, J., Coelho, E., Farias, V., & Freitas, L.: “Didactic platform for teaching of three-phase rectifier circuits in power electronics”. International Journal of ElectricalEngineeringEducation, Vol. 51, No. 4(2014), 279-291.

[13] Bermúdez C.: “Diseño y construcción de un módulo didáctico de control analógico con controladores de tipo adelanto-atraso”. Tesis de Pregrado, Universidad de Los Andes, Mérida – Venezuela(2017).

[14] Serra, G.: “Experimental approach applied to practical classes on digital control systems: a contribution from model-based control theory”. The International Journal of Electrical Engineering & Education, Vol. 57, No. 2(2020), 99-132.doi: 10.1177/0020720918788723

[15] Takács, G., Gulan, M., Bavlna, J., Köplinger, R., Kováč, M., Mikuláš, E., & Salíni, R.: “HeatShield: a Low-Cost Didactic Device for Control Education Simulating 3D Printer Heater Blocks”. In: IEEE (ed), 2019 IEEE Global EngineeringEducationConference (EDUCON), (2019), 374-383.

[16] Sánchez J.: “Diseño y construcción de un controlador PID analógico”.Tesis de Pregrado, Universidad de Los Andes, Mérida – Venezuela(2009).

[17] Pruna, E., Chang, O., Jiménez, D., Pérez, A., Ávila, G., Escobar, I., & Gordon, A.:“Building a training module for modern control”. In: IEEE (ed), 2015 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON), (2015), 369-373.

[18] Oltean, S., Dulău, M., & Duka, A.:“Didactic system for the experimental study of digital pid control structures”. Scientific Bulletin of the PetruMaior University of TarguMures, Vol. 13, No.2 (2016).

[19] Andrade, R.: “Módulo didáctico para controlar nivel y caudal de agua, mediante sistema SCADA, PLC y algoritmo PID”. Revista de Investigaciones en Energía, Medio Ambiente y Tecnología, Vol. 4, No.2 (2020), 50-62.

[20] Barba, C., & Eduardo, R.: “Desarrollo de práctica de automatización a través de un módulo didáctico con el plcsimatic s7-1200 para el control de electroválvulas”. Tesis de Grado, Universidad Técnica de Cotopaxi, La Mana – Ecuador (2017).

[21] Koleff, L., Valentim, G., Rael, V., Marques, L., Komatsu, W., Pellini, E., & Matakas, L.: “Development of a Modular Open Source Power Electronics Didactic

Platform”. In: IEEE (ed), 2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC), (2019).

[22] Chávez, J., & Díaz, L.: “Work in Progress: Design and implementation of a didactic module with manual interface, PLC interface and PC serial interface for teaching process control techniques”. In: IEEE (ed), 2019 IEEE World Conference on Engineering Education (EDUNINE), (2019).

[23] Magos, M., Chávez, J., Flores, Z., Sánchez, M., Zúniga, R., & Espinoza, D.: “Tablero didáctico para prácticas con controladores lógicos programables”. Pistas Educativas, Vol. 38, No. 120 (2018).

[24] Dorf R &Bishop R.: “Ingeniería de control moderna”. PEARSON Prentice Hall, México 1998.

[25] Fairchild Semiconductor. “Datasheet LM78XX/LM78XXA 3-Terminal 1 A Positive Voltage Regulator”, Fairchild Semiconductor Corporation (2006).

UNIVERSIDAD
DEL ZULIA

REVISTA TECNICA

OF THE FACULTY OF ENGINEERING
UNIVERSIDAD DEL ZULIA

Vol. 43. N°3, September - December 2020

This Journal was edited and published in digital format on August 31st 2020 ***by Serbiluz Editorial Foundation***

www.luz.edu.ve
www.serbi.luz.edu.ve
www.produccioncientifica.org