Compensators design utilizing the frequency response methods and generating a summary report in Latex: Interactive Graphical User Interface

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ABSTRACT

An important task for a professor in control engineering is to transfer knowledge to students in classroom in a formal and logical way. One of this knowledge is the response-frequency methodology that is used to design different types of compensators. This article introduces an interactive graphical user interface to design compensators (phase-lead, phase-lag, phase lag-lead) by the technique called Trial and error and by the Analytical technique for the listed above compensators, as well as for the PI, PD and PID. MATLAB®/GUIDE was used to create this interactive interface, which was adequated to help professors and students in the study, analysis and design of different compensators; to have an insight about the indirect relationship between performance parameters on time with the frequency performance parameters and generates a summarized report in LATEX with all plots and data simulations. Fifty percent of all students that use this interface agree that it works very well to improve their understanding of the compensator design.

Keywords: *Frequency response method, Interactive user interface, Compensator, MATLAB®/GUIDE, LATEX.*

1. INTRODUCTION

The development of an interactive interface is growing during the last decades, with application in the control systems theory. New methods and pedagogical practices are the major challenge for professors in educational areas of control engineering. The main challenge in teaching of the control system theory is the need to enable students with strong theoretical foundation and engineering skills. The theoretical basis can be taught in a regular classroom, but the engineering skills can be obtained from lab works [1], [2], [3]. Laboratory teaching in the control system area is quickly growing in the last three decades, due to the development of the Information and Communication Technology. A characteristic of this technology is the interactivity, which motivates the innovation of teaching methods. The teaching scenario of the control systems theory in engineering education is based in the development of interactive tools utilizing MATLAB [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], Java [12], LabView [13], C/C++ [14], MATHEMATICA [15], Maple and MATLAB [16]. Control system disciplines are part of the curriculum of different engineering courses and their main objective is to consolidate the concepts of control system analysis, as well as the controller design. The frequency response of a control system reveals a qualitative frame of the transient response. In the closed-loop design, the frequency response characteristic of the open-loop transfer function is adjusted using some design criteria in order to obtain plausible transient-response characteristics for the system. Nyquist, Bode and Nichols developed the three well-known frequency domain methods in 1930s and 1940s [17], [18]. We can understand by frequency response as the steady-state response of the system submitted to a sinusoidal input whose frequency is varied over a certain range of interest.

The Bode diagram is one of the graphical represent-ations of the frequency-response characteristics of a system. A Bode diagram represents the sinusoidal transfer function in two separate plots, where one plot gives the magnitude (in dB) versus frequency and the other plot gives the phase angle (in degrees) versus frequency. In both plots, the frequency is in rad/s, and in a logarithmic scale. In this article it is utilized the Bode diagram approach to design all compensators because it is simple to add the compensator to the Bode diagram [19], [20], [21], [22].

MATLAB® is a programming environment for developing algorithms for scientists and engineers in different research areas and it allows you to create graphical user interfaces (GUI). GUIDE is a graphical user interface designed environment in MATLAB® and it provides tools for designing a user interface that uses the MATLAB codes and commands [23].

In this article it is shown an interactive user interface carried out in MATLAB® /GUIDE. The Bode diagram approached to the frequency response methods is used to implement the design procedure presented in [21] for phase-lead, phase-lag, phase lag-lead and phase lead-lead compensators, as well as the design procedure in [22] not only for the above mentioned compensator, but also for the PI, PD and PID compensators. These two different design procedures were developed for the interface. For the first it was used the Bode diagram approach and for the last one it was used the Nyquist diagram.

The interactive interface is useful for the compensator design for simple-input simple-output linear invariant time systems. The graphical user interface presented in this article aims to help the professors in classroom lessons, and students into a fortified understanding of theoretical principles through simulations and interactive practice, as well as it shows the control effort, considered an important information. Due this, it is possible to know how much of the control variable is needed to stabilize the system under study, but this variable is forgotten in most applications referenced in this paper. Also, this interface engenders a report in LATEX with all data simulation, i.e., design data and performance parameters in a .tex file and figures of all simulation in .jpg files.

This article is organized as follows: in section 2 the analytic technique procedure of a compensator design is introduced and summarized according to [22]; in section 3 it is described the interactive interface, as well as how the user can use this one showing a practical example; in section 4 it is the pedagogical experience; and finally in section 5 it shows Discussions and Conclusions.

2. PHASE-LEAD COMPENSATOR DESIGN PROCEDURE

Compensation in control system is defined as the choice, design and settling of devices that are included in this system in order to satisfy the performance specifications. These devices are known as compensators. The role of the compensator is to improve the transient response of a system, as well as

the steady-state error characteristics. In this article, the compensator is placed in cascade with the system such that it is compensated, see Figure 1.

Approaches used for the interactive user interface shown in this article are based on the methodologies described in [21], [22] for cascade compensators design. These methodologies are denominated as "Trial and error technique" and "Analytical technique". As an illustration, a summary of the design procedure shown in [22] for the lead compensator is described as it follows.

Consider a unity negative feedback system shown in Figure 1, where G(s) is the open-loop transfer function of the plant, Gc(s) is the cascade compensator transfer function, C(s) is the Laplace transform of the system output and R(s) is the Laplace transform of the system input.

In [22] it is shown an analytic procedure of different compensator designs, and it is summarized here. This procedure adjusts the phase margin of the system with more accuracy. The dc gain is determined from the velocity static error constant requirement, and it is supposed that there is a first order compensator so that satisfies the design requirement.
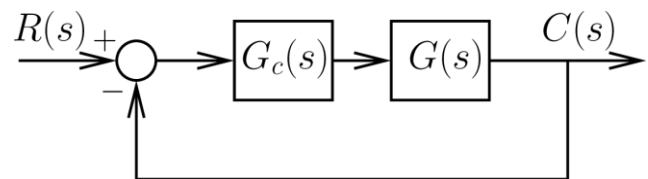

Fig. 1. System with cascade compensator.

For the development of the design equations, it is assumed that the Nyquist diagram of the compensated system has the form shown in Figure 2. Consider that the characteristic equation of the system is

$$1 + G_c(s)G(s) = 0 \qquad (1)$$

and the compensator transfer function is given by

$$G_c(s) = K_c \frac{n_2 s + 1}{d_2 s + 1} \qquad (2)$$

Note that the desired phase margin (PM) has been reached at the frequency ω_1 and from Figure 2 is obtained

$$G_c(j\omega_1)G(j\omega_1) = 1 \angle(-180^o + PM). \qquad (3)$$

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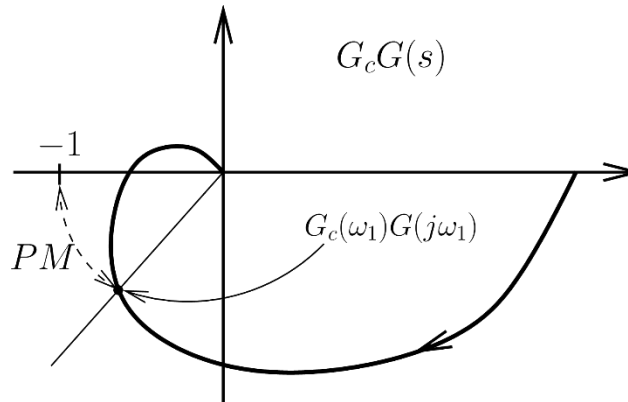M. E. M. Meza and F H G Zucatelli

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$$G_cG(s)$$

Fig. 2. Compensated Nyquist diagram.

It is desired to determine the compensator coefficients n_2 and d_2 such that Eq. (3) is satisfied for a specific compensator dc gain K_c. From Eqs. (2) and (3) it is obtained

$$G_c(j\omega_1)G(j\omega_1)$$
$$= K_c\left(\frac{n_2s+1}{d_2s+1}\right)_{s=j\omega}G(j\omega_1)$$

$$G_c(j\omega_1)G(j\omega_1) = K_c\left(\frac{jn_2\omega_1+1}{jd_2\omega_1+1}\right)G(j\omega_1)$$

$$G_c(j\omega_1)G(j\omega_1) = 1\angle(-180^o + PM). \quad (4)$$

Expanding Eq. (4) into two equations by equating real and imaginary parts of the complex expression. There are four unknowns in Eq. (4), which are K_c, n_2, d_2 and ω_1. Let θ be the angle of $G_c(j\omega_1)$, and from Eq. (4) obtains

$$\theta = \angle\big(G_c(j\omega_1)\big) = -180^o + PM - \angle\big(G(j\omega_1)\big). \quad (5)$$

and after some algebraic manipulation the design equations are

$$n_2 = \frac{1 - |G(j\omega_1)|\cos\theta}{|G(j\omega_1)|\omega_1\sin\theta} \quad (6)$$

$$d_2 = \frac{\cos\theta - |G(j\omega_1)|}{\omega_1\sin\theta} \quad (7)$$

There is a compromise between n_2, PM and t_s such that the compensated system has the appropriate stability characteristics. For the phase-lead compensator the design procedure has the following steps:

1) The phase compensator, θ, must be positive

$$\theta = \angle\big(G_c(j\omega_1)\big) = -180^o + PM - \angle\big(G(j\omega_1)\big) > 0$$

i.e., the frequency ω_1 must be chosen to satisfy the phase condition

$$\angle\big(G(j\omega_1)\big) < -180^o + PM. \quad (8)$$

2) The choice of ω_1 must satisfy the gain condition

$$|G(j\omega_1)| < 1. \quad (9)$$

3) In the transfer function $G_c(j\omega_1)$, parameters n_2, d_2 must be positive. Since $\sin\theta > 0$ for the phase-lead compensator and from (6) and (7), we obtain

$$\cos\theta > |G(j\omega_1)|. \quad (10)$$

To achieve the desired phase margin, the choice of ω_1 must satisfy the constraints Eqs. (8), (9) and (10) for the phase-lead compensator.

3. INTERACTIVE GRAPHICAL USER INTERFACE

To initiate the interface for the design of the different compensators the following commands must run in the windows command MATLAB or in a 'm' file.

```
%% Cleaning

clear all, close

all, clc %% Example
% Numerator
coefficients of %
the transfer
function n=1;
% Denominator coefficients
of % the transfer function
d=conv([1 0],conv([0.1
1],[1 1]));
%% Defining System
MySys=tf(n,d);
%% Open Main Screen
main
```

Figure 3 shows the main screen of interface, where it is possible to choose the design procedure method, that is: Trial and error technique or Analytical technique. On the "Analytical technique" menu, it is possible to choose the type of compensator, that is: Phase-lead, Phase-lag, Phase lag-lead, Phase lead-lead, PI, PD, PID compensator, see Figure 3.

Figure 4 shows the user interface for the design and simulation of the phase-lead compensator utilizing the analytic technique. Consider an example with open-loop transfer function G(s) = 1/ (s(0.1s + 1)(s + 1)). It is desired to design a phase-lead compensator for the system, so that the static velocity error constant Kv is 4 s⁻¹, the phase margin is at least 45° and the gain margin is at least 10 dB.

In Figure 4, on the "Design parameter" menu, it is possible to choose the parameters that can be used to design the compensator. Among these parameters are: Kv (static velocity error constant), PM (desired phase margin), Mp (maximum overshoot), ts (settling time) and BW & ts (bandwidth and settling time). Choosing the following parameters Kv and PM and entering the respective values in appropriated boxes.
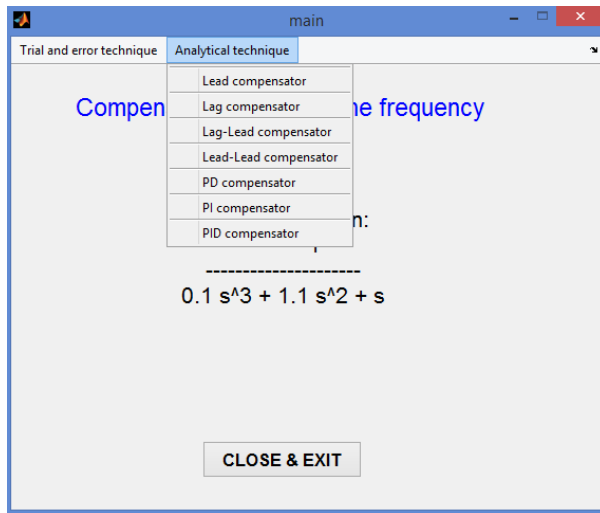

Fig. 3. Menu content of Analytical technique.

The "Plant" panel, see Figure 4, has input boxes where the numerator and denominator coefficients of the open-loop transfer function of the system are shown or are entered. By clicking the "Bode Open Loop" button, it is displayed the Bode diagram, the Step response of the closed-loop system and the

Control effort needed to the output system tracks the step input and it is possible to observe that the margin phase of the uncompensated system is PM = 47.4°, the gain margin is GM = 20.8 dB, Mp = 20.6%, ts = 8.5 s. The "Adjusted Gain" panel has an input box where the static velocity error constant value is entered, and by clicking the "Bode OL + Adjusted Gain" button, it is displayed the value of the Kc gain and the respective Bode diagram, the Step response of the closed-loop adjusted gain system and the Control effort needed to the output system tracks the step input.

The "Lead Compensator" panel, see Figure 4, has output boxes where are shown the exponential of the lower and the higher frequency presented in the Bode diagram. Alternatively, it is possible to enter new values for these bounded exponential frequencies, it is also shown that the desired PM and the respective designated value can be entered, and by clicking the "Determine compensator" button it is determined the "Desired parameters", which are theta (θ), wcg (gain crossover frequency), zeta (desired damping coefficient) and Mp (maximum overshoot) and the "Compensator coefficients". Alternatively, it is possible to enter new compensator coefficient values, which can be used to the simulation of the compensated system.

Figure 4 shows the "Bode OL + Gain + Compensator" button and results by clicking it, the interface displays the Bode diagram, the Step response of the closed-loop system and the Control effort needed to the output system tracks the step input of the compensated system.
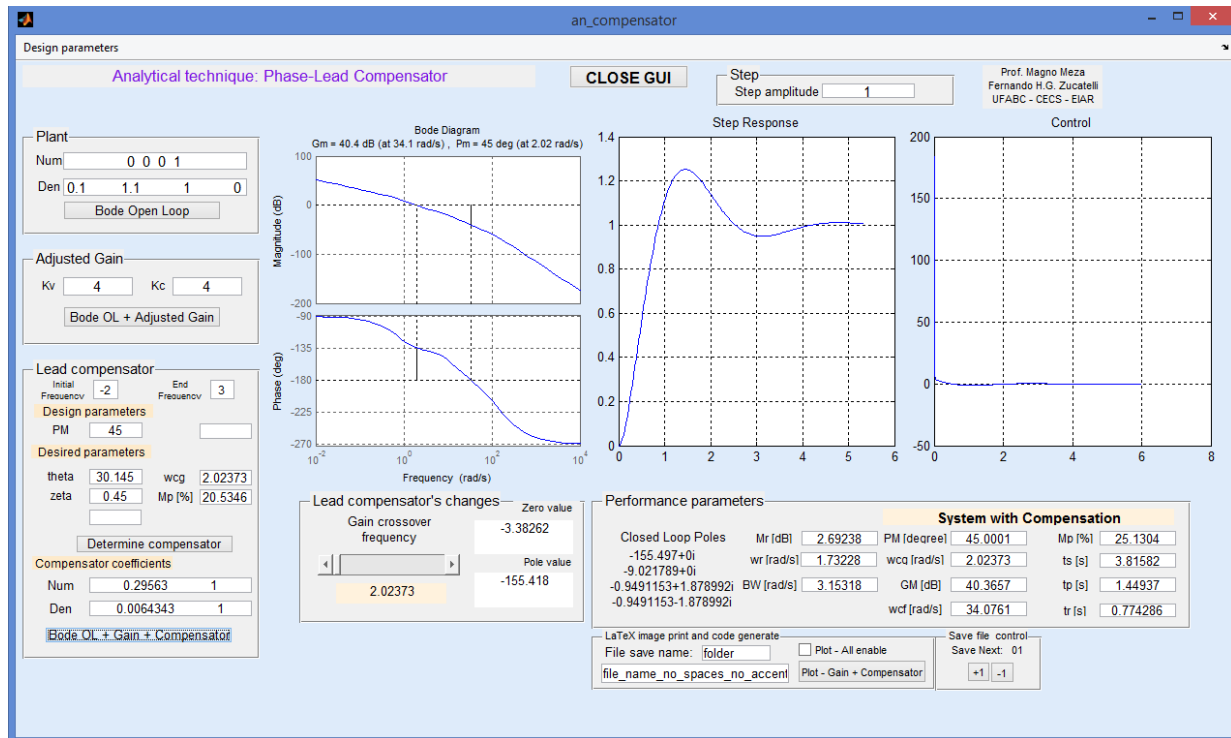
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Fig. 4. Simulation of the compensated system.

The "Lead compensator's changes" panel, see Figure 4, has a slider bar with which the frequency value of ω_1 can be changed by sliding the slider bar. At the same time, it changes the value of theta in the "Lead compensator" panel, the zero and pole values of the compensator. The "LaTeX image print and code generate" panel, where the "`Plot - ...`" button saves the figures at the specified "folder" which it should exist before applying this command or it should be given in an empty string at its box. The files can be saved at the same folder where the program is, and applies some prefix and suffix to the name given at the `file_name_no_spaces_no_accents` textbox. The user defines the project by naming it and has all the results separated and automatically organized. It also stores a `.mat` file with the string `str_latex` that generate the LATEX report and main data for late use.

The `.tex` file is automatically created and it indicates the method and type of each graph, organizing each set of parameters and resulting as numbered equations.

The text and background color of the button change according to the last plotted graph and keep itself

until another graph is plotted, or the "`Plot - All Enable`" checkbox be checked. This checkbox gives the simple option to store all the project development in a single click and when the "`Plot - ...`" button is pressed to save all results, the number at the "`Save next`" panel is updated. The user can still change the number as he/she wants by clicking on "-1" and "+1" buttons. This is a possibility to "`redo`" any wrong or undesired plot made before, but any result with the same name given by the same `file_name_no_spaces_no_accents` core will be overwritten.

4. PEDAGOGICAL EXPERIENCE

The interface in its first version was used in classroom as part of EN2710: Control Systems II undergraduate level course taught at the Federal University of ABC from September to November, 2015. Students response have been positive and it helps to improve the interface to obtain the current version, which was tested and evaluated by students.
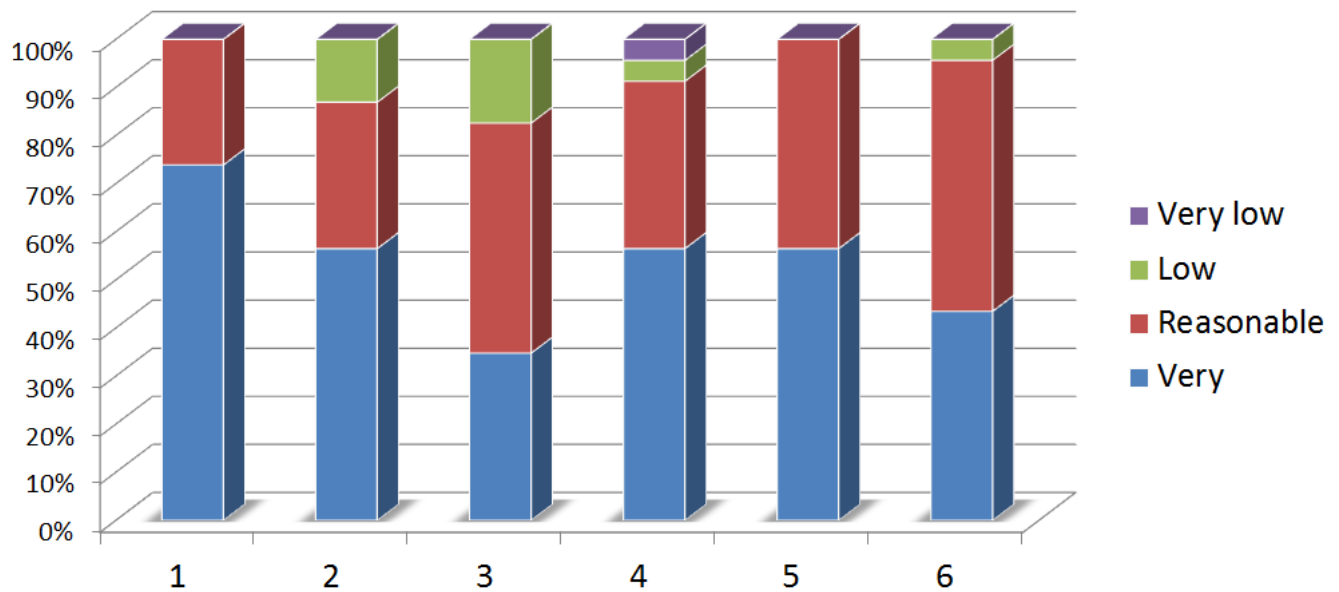
Fig. 5. Students questionnaire results about the use of interface, for Question 1 to 6.

The interface is used to the theoretical discussion of design procedure for different compensators in discipline EN2710,

as well as it is used to design the lead, lag and lag-lead that implement in the didactic kit of Quanser®.

The interface was tested with 23 students coming from the Control System II. Students were required to fill out an evaluation questionnaire with six multiple-choice questions about the interface, see Table 1.

Figure 5 shows that for Question 1, 70% of students believe that the interface is very appropriated and a 30% believe that it is reasonable appropriated to compensator design; for Question 2, 50% of them agree that the interface is very easy to use, 30% agree that it is reasonable easy to use and 20% agree that it is less easy to use; for Question 3, authors believe that the last topic is due to that 30% students that are very motivated to use it, 50% are reasonable motivated to and 20% are low reasonable motivated to use the interface; for Question 4, 50% of them agree that the interface works very well to improve their understanding of the compensator design, and 40% of them agree that it works reasonably well to improve their understanding; for Question 5, 50% of them are very satisfied with the interface and 50% are reasonably satisfied with it; and for Question 6, 40% of them recommend a very frequently the use of interface, 50% of them recommend a reasonable frequently the use of it. Some troubles could be solved if the interface had a help button for quick access, so students were not discouraged to use it; there is a user manual of the interface (in Portuguese) which was available to students, as well as in the

future, authors intended to explain the interface in one or two classes so that students feel secure. Interface questionnaire, in Table I, was inspired by [24], [25].

Table 1: Interface questionnaire to obtain students' feedback.

Q1. How appropriate was the interface for you to learn about the compensator designs?
Q2. How would you qualify the usability of the interface (user-use facility)?
Q3. What was your level of motivation to use the interface in the compensator design?
Q4. How well did the interface improve your understanding of the compensator design?
Q5. In general, what is your level of satisfaction about the interface?
Q6. How frequently would you recommend the use of this interface?

5. DISCUSSIONS AND CONCLUSIONS

The interactive graphical user interface presented in this article is an update version of the described in [26]. In the current version it was included more one graphic axes to plot the control effort, as well as the procedure of analytic technique and the "Lead compensator's changes" panel. "LATEX image print and code generate" panel saves and exports data simulations and plots, and generates a summarized Latex report as can be seen in Appendix.

In control systems it is important the transient-response performance. In frequency response methods the transient-response performance is specified in terms of the phase margin, gain margin, resonant peak magnitude, gain crossover frequency, resonant frequency, bandwidth, and static error constant. The correlation

between transient-response and the frequency response is indirect, due to this, this interface favors the understanding of this correlation for the students.

After the compensator was designed it is necessary to check whether the compensated system satisfies the requirements in the time domain. If it does not, then the compensator must be recalculated or if it is possible to change the position of its pole and/or zero. It can be done in this interface, when the slider bar "Gain crossover frequency" is sliding and with this, the crossover frequency ω_1 is changed such that new values of pole and zero of the compensator are obtained to the new simulations. Comparing performance parameters in Figure 4, it can be concluded that the system in Figure 4 has a gain margin of 40.4 dB and it is needed a control effort of 200 units. If the frequency ω_1 is changed from 2.02 rad/s to 4.02 rad/s, the system for this new gain crossover frequency has a gain margin of 12 dB and it is needed a control effort of 50 units. With this, the gain margin is reduced and so the control effort either and for a practical application is more convenient to use a lower control effort than a higher one.

The control effort is an important information in real system, because it is needed to know if it is possible to apply this control in the system, such that it does not damage the real plant with an overhead value. With this information is possible to redesign the controllers, such that they are within a range of values or that the saturation time of them is the shortest possible.

From Figure 4 and Tables II and III, it can be concluded that if the transfer function of a system has a pole with high value the control effort will be high too, and compared the settling time will be less for the system with smaller poles, as well as it also verifies that with the modification of crossover frequency (ω_1), the band width was increased such that the settling time (ts) was reduced.

In [8] is shown an interactive interface made in MATLAB$^{®}$ that it uses the frequency response to design the compensators and the methodology used is shown in [19]. In the current interface is possible to choose between two methodologies presented in [21] and [22], and the lead-lead compensator is available for both methodologies, but the interface is not connected to a real plant. The interface is versatile because all designed parameters of the compensators can be changed manually, e.g., changing the gain crossover frequency w1 changes the pole and zero values of the compensator according to the Analytical technique stated in [22], and for the Trial and error technique stated in [21] the pole and zero values can be changed independently of one another. The interface is used by students to design the different compensators, which will be implemented in the didactic kit "Linear Motion Servo Plant" of the Quanser.

In summary, the interface is a versatile tool that improve the understanding of students that uses it to design of the different compensators, and the professor can use this interface in classroom to better explain the influence of the compensators in a generic system. Also, can be used to the understanding of the indirect relation between the performance parameters in time domain with the performance parameters in the frequency domain.

Additional features of the interface are being developed by the authors, e.g., language choice, the ability to compare the system response for two different compensators, among others.

Appendix: Results latex

This section is created with data and figure on the project sequence. Here we reorganized the text to be more compact and agree with this paper cross references. Therefore, there are no figures on this section. In Table II is shown all performance parameters of the system according to the design sequence. The simulation figures are not shown here, although they are presented at the generated report.

The numerator and denominator coefficients of the lead compensator are

$$\text{Num} = \quad [0.29563 \quad 1]$$
$$\text{Den} = \quad [0.0064343 \quad 1]$$

and the zero and polo values of lead compensator are:

$$\text{Zero value} = -3.38$$
$$\text{Pole value} = -155.42$$

according to Figure 4 and Table II.

Data for the system with different lead compensator, see Table III. The numerator and denominator of the different lead compensator are

$$\text{Num} = \quad [1.2109 \quad 1]$$
$$\text{Den} = \quad [0.11845 \quad 1]$$

and the zero and pole values are

Zero value = -0.83

Pole value = 8.45.

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Table 2: Comparison of performance parameters of the uncompensated, with adjusted gain and compensated system.

System without gain	System with adjusted gain	Compensated system
-10.11+0i	-10.41+0i	-155.50+0i
-0.45+0.89i	-0.30+1.94i	-9.02+0i
-0.45-0.89i	-0.30-1.94i	-0.95+1.88i
		-0.95-1.88i
	Kv=4.00	Kv=4.00
Mr[dB] = 1.24	Mr [dB] = 3.297	Mr [dB] = 2.69
wr[rad/s] = 0.77	wr[rad/s] = 1.91	wr[rad/s] = 1.73
BW[rad/s] = 1.32	BW[rad/s] = 2.98	BW[rad/s] = 3.15
PM[degree] = 47.4	PM[degree] = 17.7	PM[degree] = 45.0
wcg[rad/s] = 0.78	wcg[rad/s] = 1.86	wcg[rad/s] = 2.02
GM[dB] = 20.83	GM[dB] = 8.79	GM[dB] = 40.37
wcf[rad/s] = 3.16	wcf[rad/s] = 3.16	wcf[rad/s] = 34.08
Mp[%] = 20.60	Mp[%] = 60.75	Mp[%] = 25.13
ts[s] = 8.484	ts[s] = 13.24	ts[s] = 3.82
tp[s] = 3.65	tp[s] = 1.70	tp[s] = 1.45
tr[s] = 2.06	tr[s] = 0.81	tr[s] = 0.77

Table 3: Performance parameters of the compensated system with different gain crossover frequency.

Different compensated system
-14.60+0i
-2.02+4.99i
-2.02-4.99i
-0.80+0i
Kv = 4.00
Mr[dB] = 2.47
wr[rad/s] = 4.45
BW[rad/s] = 7.10
PM[degree] = 45.01
wcg[rad/s] = 4.01
GM[dB] = 11.95
wcf[rad/s] = 9.36
Mp[%] = 22.77
ts[s] = 1.68
tp[s] = 0.71
tr[s] = 0.40