ISSN: 2594 - 2905

DESIGN GUIDE OF A FEEDFORWARD COMPENSATOR FOR A BANDPASS FILTER AS A COMPLEMENT TO LEARNING IN CONTROL THEORY

DESIGN GUIDE OF A FEEDFORWARD COMPENSATOR FOR A BANDPASS FILTER AS A COMPLEMENT TO LEARNING IN CONTROL THEORY

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https://doi.org/10.61117/ipsumtec.v7i2.311

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Abstract -- This research proposes a module to support the learning of students in the subject of control, the complexity in students to understand the use of compensators to control systems is the point to consider in this research, the proposed control system is a bandpass filter with a specific frequency range which will be designed a compensator in frequency using bode plots and the procedure discussed in the book of OGATA, The development of the proposed module is corroborated through the Multisim software, Matlab, and the mathematical procedure, thus obtaining the characteristics of the compensator to reach the desired values in the compensation, is considered as support the subject of control because it is a guide on how to design a compensator in advance step by step for the to reach a metacognitive process.

Keywords: learning, compensation, Bode diagram, filter, gain.

Abstract -- The present investigation proposes a module to support the learning of the students in the subject of control, the complexity in the students to understand the use of the compensators to the control systems is the point to consider in this investigation, the proposed control system It is a bandpass filter with a specific frequency range for which a frequency compensator will be designed using the bode graphs and the procedure discussed in the OGATA book, the development of the proposed module is corroborated through the Multisim software, Matlab, and The mathematical procedure, thus obtaining the characteristics of the compensator to reach the desired values in the compensation, is considered as support for the control subject because it is a guide on how to design a compensator in advance step by step so that the student reaches a metacognitive process.

Key words - Bode plot, compensation, filter, gain, learning.

INTRODUCTION

Control theory has had great contributions and advances to the area of engineering, "it has become an integral part of space vehicles, in robotic systems, in modern manufacturing processes and in any industrial operation that requires control of temperature, pressure, humidity, flow, etc." OGATA, therefore, it is desirable that engineers have the knowledge and management of control in its different variants.

Classical control or conventional control is the first contact that students have with the subject, it begins with the introduction of concepts and then introduces topics such as modeling of mechanical, electrical, pneumatic, etc. systems. It continues with the response to singular functions and then compensate its output with the design of PI, PD, PID compensators and thus be able to reach what is the frequency response of different systems and also design and implement filters in advance, delay and advance-delay and advance-delay.

Modern control theory is based on the analysis in the time domain of systems of differential equations OGATA, this theory facilitated the modeling of systems as it is more realistic. However, the

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system stability is affected and it is here that robust control can be applied, but a more rigorous analysis is required to analyze it.

Bringing control theory to the classroom is of great importance for engineers and future engineers, so having a support that facilitates the teaching-learning process will have an impact on cognitive knowledge, the lack of prior visualization of control actions hinders the understanding of the purpose to be achieved, which leads us to our goal which is to design a didactic module that facilitates the student's understanding of control theory.

Other methods have been implemented for teaching-learning of control theory as the design of an activity for an automatic control course based on mathematical modeling GUZMÁN 2019 in which proposes a methodology based on a path of study and research (REI) prioritizing the development of three stages for the control of the speed of an engine and establishes a relationship between mathematical and non-mathematical through its activity, this aimed at a theoretical and practical teaching. The didactic module proposed in this paper leads the student to a visualization of what is to be achieved by applying control theory in the classroom, thus achieving significant learning.

In the development of the module is created for a band pass filter that is considered as the plant or system to work, it is designed to work at frequencies from 15.31Hz to 743.83Hz, its bode response is analyzed to know the characteristics of the system and thus, design and implement the compensator in advance.

DEVELOPMENT

Methodology.

1.- Creation of the band-pass filter.

In a band-pass filter, there are two main configurations, passive and active; the passive filter is that one which is designed and composed only of resistors and capacitors and does not amplify the input signal, by the The active filter, on the other hand, is designed and composed by resistors, capacitors y a amplifier

The first step was to design a band-pass filter, which amplifies and phase-shifts the signal. First, a band-pass filter was designed.

based on U741, in this case the cut-off frequencies are 15.31 Hz and 743.83 Hz.

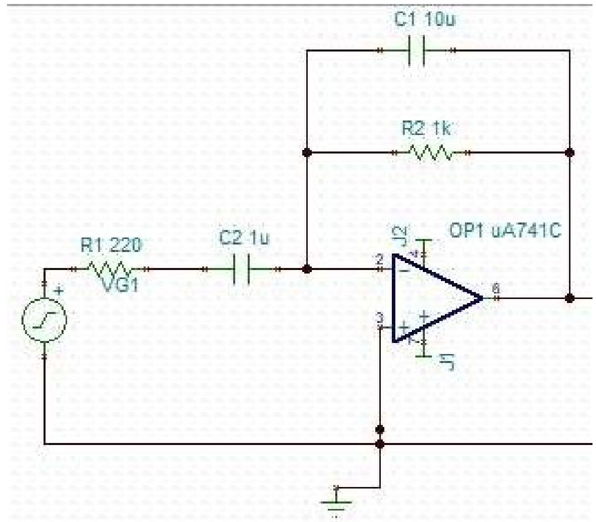

Figure 1. Bandpass filter.

In order to analyze the bode diagram it is necessary to calculate the transfer function. In order to simplify obtaining the transfer function, an impedance approach will be used as shown in Figure 2.

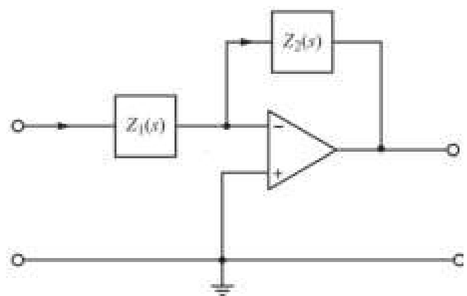

Figure 1. Impedance approach.

In equation 1 we have the simplified form to calculate the transfer function.

Z_1 and Z_2 with equations 2 and 3.

$$\frac{V_o(s)}{V_i(s)} = -\frac{Z_1(s)}{Z_2(s)} \qquad \text{Eq. (1)}$$

Where

$V_o(s)$: Output voltage
$V_i(s)$: Input voltage

$$Z_1 = R_1 + \frac{1}{C_1S} = \frac{1+R_1C_1S}{C_1S} \qquad \text{Eq. (2)}$$

$$Z_2 = \frac{\frac{R_2}{C_2S}}{R_2+\frac{1}{C_2S}} = \frac{\frac{R_2}{C_2S}}{\frac{1+R_2C_2S}{C_2S}} = \frac{R_2}{1+R_2C_2S} \qquad \text{Eq. (3)}$$

The transfer function is calculated

$$G(s) = -\frac{\frac{R_2}{1+R_2C_2S}}{\frac{1+R_1C_1S}{C_1S}} = \frac{R_2C_1S}{1+R_1C_1S+R_2C_2S+R_1R_2C_1C_2S^2} \qquad \text{Eq. (4)}$$

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Now we proceed to replace the values of the components used.
Therefore, the transfer function of this filter is as follows:

$$G(s)=\frac{1ms}{2.2\mu s^{2}+10.22ms+1} \qquad \text{Eq. (5)}$$

With this transfer function, the Bode diagram is plotted.

```
%Función de transferencia filtro
a=[-0.001 0];
b=[0.0000022 0.01022 1];
w=tf(a,b)
```

Figure 3. Matlab code for the filter.

The following graph shows the magnitude and phase graphs.

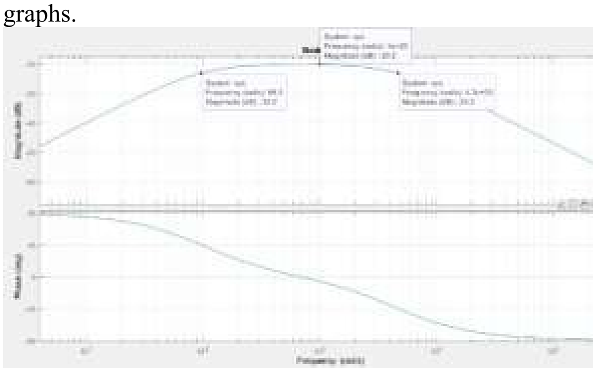
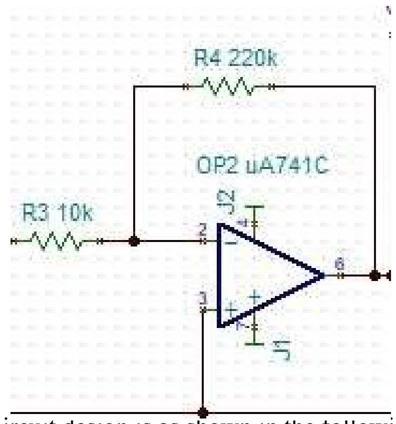


Figure 4. Bode diagram of the filter in Matlab.

As can be seen in Figure 4, the magnitude plot is not crosses zero, therefore, a phase margin cannot be calculated.

2.- Filter with amplifier to adjust the gain.
For the design of a forward compensator, it is necessary that the frequency response of the filter exceeds a gain of 0dB. To achieve this gain, another amplifier is added by calculating the gain to raise the magnitude in dB.
This process is done by placing an operational amplifier with two resistors as shown in the following image.



The new circuit design is as shown in the following image.

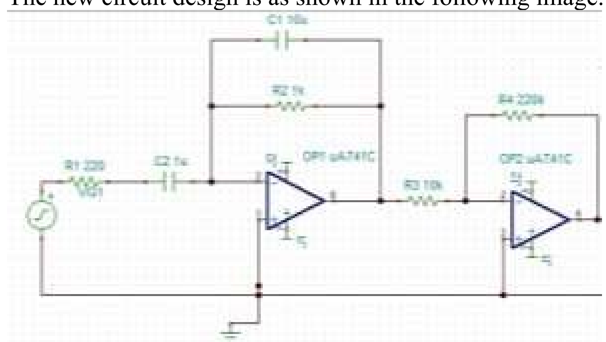


Figure 6. Filter with amplifier.

Again, the transfer function is calculated.

$$FT=\left(\frac{R_2C_1S}{1+R_1C_1S+R_2C_2S+R_1R_2C_1C_2S^2}\right)\left(\frac{R_4}{R_3}\right)= \qquad \text{Eq. (6)}$$

```
%Función de transferencia filtro
a=[-0.001 0];
b=[0.0000022 0.01022 1];
w=tf(a,b)

%Función de transferencia Amplificador
c=[-22000];
d=[1000];
m=tf(c,d)
r=w*m
```

Figure 7. Matlab code for the filter with amplifier.

Figure 8 shows the Bode diagram of the filter with gain adjustment, in which there is already a zero crossing.

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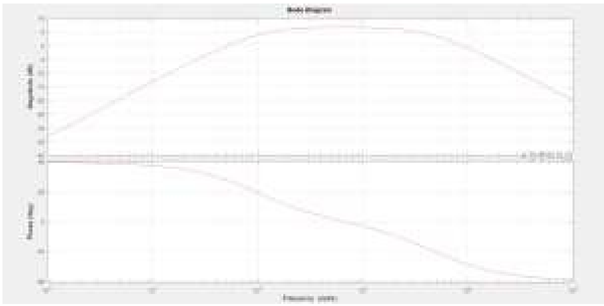

Figure 8. Bode diagram of the filter with amplifier. 3.- Design of the forward compensator.

At this point a compensator can be applied to the initial system. First, the following circuit composed of operational amplifiers, capacitors and resistors was made:

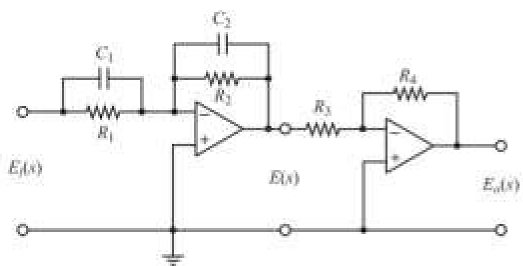

Figure 9. Compensator.

The following steps were followed for the design of the forward compensator.

1. First set a desired phase margin to be reached after compensation.

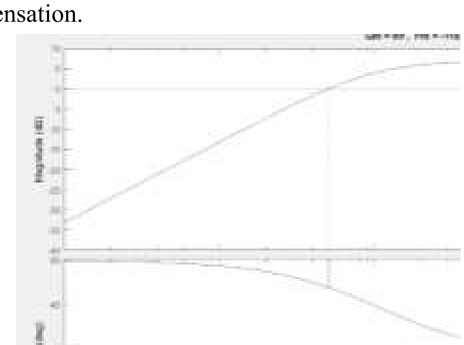

Figure 10. Plant phase margin.

The phase margin was calculated, as shown in the image 10, and a measurement of 118° is obtained.

M_ϕ of filter: 118°.
M_ϕ desired: 145°.

145°-118°=27°

2. Determine the phase advance angle that needs to be added to the system. Increase an additional 5° to 12° phase advance to the required phase advance angle.

27°+12°=39°

3. The attenuation factor is then calculated.

$$\alpha = \frac{1-seen(()(39))}{1+sen(39)} = 0.23 \qquad \text{Eq. (7)}$$

$$20 \log \left(\frac{1}{\sqrt{0.23}}\right) = 6.38dB \qquad \text{Eq. (8)}$$

4. Find at what frequency you have those 6.38 dB.

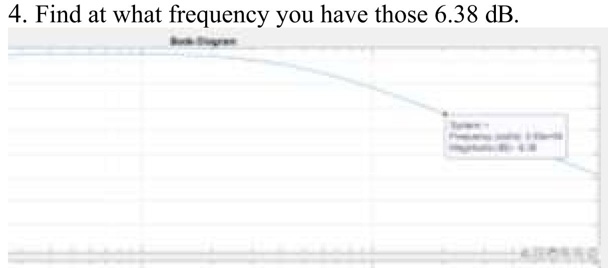

Figure 11. Location of 6.38 dB in Bode diagram.

It is at a frequency of 20.3 krad/s.

5. Calculate the zero and pole of the compensator with equations 9 and 10 respectively.

$$\frac{1}{T} = (\sqrt{0.23})(20.3krad/s) = 9.74k \qquad \text{Eq. (9)}$$

$$\frac{1}{\alpha T} = \frac{20.3krad/s}{(\sqrt{0.23})} = 42.33k \qquad \text{Eq. (10)}$$

6. The transfer function of the compensator is obtained transfer function of the compensator is obtained:

$$\frac{E_o(s)}{E_i(s)} = \frac{R_2R_4}{R_1R_3}\frac{R_1C_1s+1}{R_2C_2s+1} = \frac{R_4C_1}{R_3C_2}\frac{s+\frac{1}{R_1C_1}}{s+\frac{1}{R_2C_2}} \qquad \text{Eq. (11)}$$

$$= K_c\alpha\frac{Ts+1}{\alpha Ts+1} = K_c\frac{s+\frac{1}{T}}{s+\frac{1}{\alpha T}} \qquad \text{Eq. (12)}$$

Substituting values:

$$G_C(s) = 4.35\frac{S+9.74k}{S+42.33k} \qquad \text{Eq. (13)}$$

The compensator circuit is shown in Figure 8:

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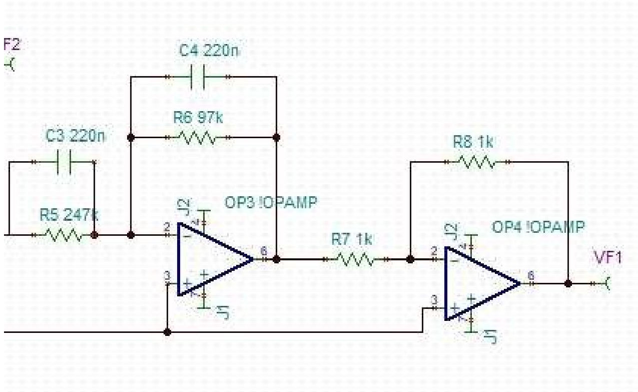


Figure 12. Compensator circuit.

7. The transfer function is plotted in Matlab, using the code shown in figure

```
%Compensador
k=[4.35];
num=[1 9740];
den=[1 42330];
```

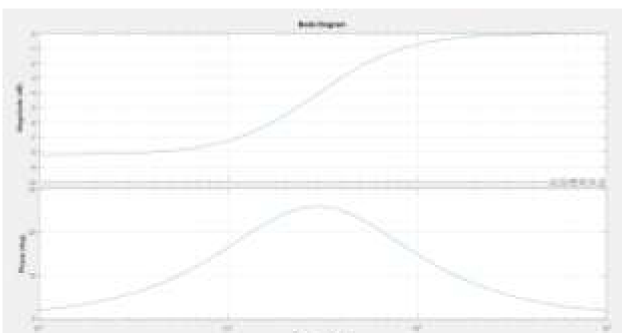
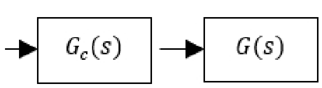


Figure 13. Bode diagram of the compensator.

7. Multiply the compensator by the initial system. It is obtained:

$$G_C(s)G(s) = 3.7\,\frac{S+9.74k}{S+42.33k}\,\frac{22s}{2.2m s^2+10.22s+1k} \quad \text{Eq. (14)}$$

$$G_C(s)G(s) = \frac{95.7s^{(2)}+932118s}{0.0022s^{(3)}+103.32s^{(2)}+433000s+42.33M} \quad \text{Eq. (15)}$$



Multiplication with blocks of the compensator and the initial system.

Compensated final system.

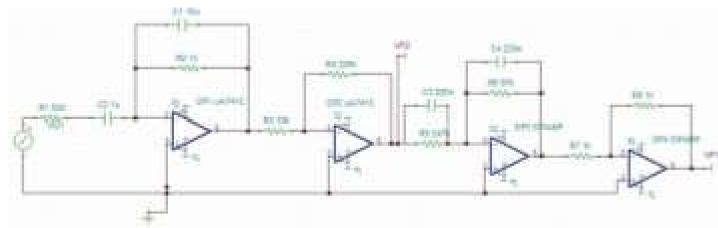


Figure 15. Final system.

```
%Función de transferencia filtro
a=[-0.001 0];
b=[0.0000022 0.01022 1];
w=tf(a,b)

%Función de transferencia Amplificador
c=[-22000];
d=[1000];
m=tf(c,d)
r=w*m

%Compensador
k=[4.35];
num=[1 9740];
den=[1 42330];

com=tf(k*num,den)
fi=r*com
hold on
bode(fi)
bode(r)
%bode(r)
%margin(fi)
```

Figure 16. Final system.

This code is used to plot the Bode diagram of the initial system and the Bode diagram of the compensated system. In Figure 17 the blue line is the plant and the red line corresponds to the compensated system.

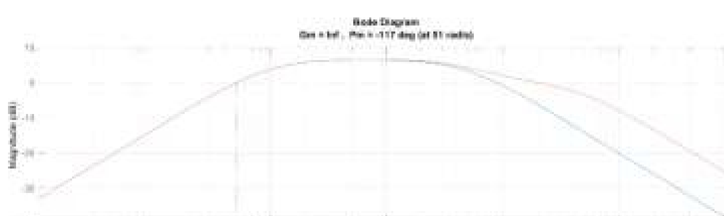


Figure 17. Final Bode diagram.

Figure 17 shows graphically the function of the compensator, which shifts the zero crossing to the right.
If it is taken into account that the addition of a feedforward compensator modifies the magnitude curve in the Bode plot, it seen that the gain crossover frequency will shift to the right (Ogata, 2010).

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Results.

Checking plant profit.

To observe how the filter works and what its gain is, a simulator is used. With the help of an oscilloscope, the input and output signals are viewed. In this case the yellow signal is the input signal and the blue signal is the output signal.

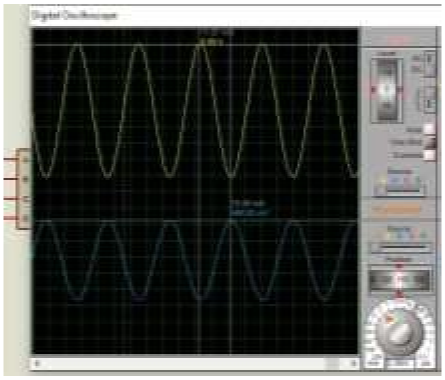


Figure 18. Simulation of the filter in Proteus.

The following formula is used to calculate the gain:

$$G = 10^{\frac{-20.2}{20}} = 0.097 \qquad \text{Eq. (16)}$$

Input signal= 5V
Output signal=(G)(Input)=(0.097)(5) =0.489mV.

These values are the ones that appear in the simulation, thus verifying that the filter has this gain.

Checking of the compensated system.

The results of the filter and compensated system are shown below, for this an input signal was placed and tests were performed at 5 different frequencies to check the operation of the plant and the compensated system.

First a point was located on the Bode diagram, and with that the angular frequency is obtained, in this case the conversion to Hz was performed.

$$\omega = 2\pi f \therefore f = \frac{\omega}{2\pi} \qquad \text{Eq. (17)}$$

The frequencies used (in Hertz) were: 118, 191, 422, 667 and 937.

In the simulator, a 3V signal and the previously mentioned frequencies were configured with a signal generator. The gain was checked with the oscilloscope. With equation 18.

$$G = 10^{\frac{dB}{20}} \qquad \text{Eq. (18)}$$

Frequency: 118 Hz

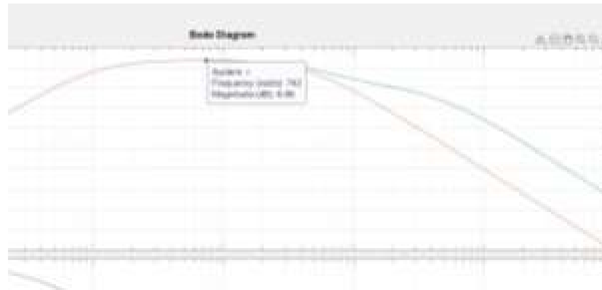


Figure 19. Bode diagram Frequency: 118 Hz

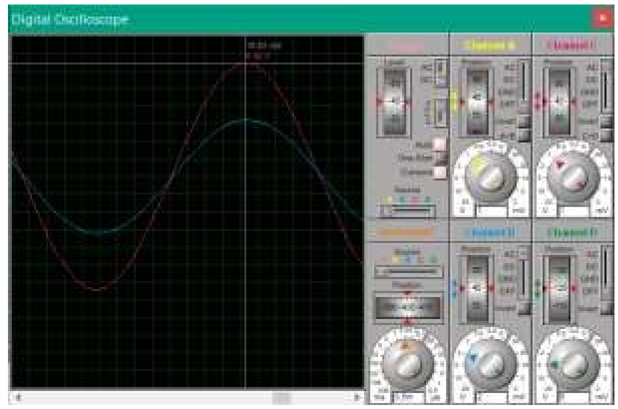
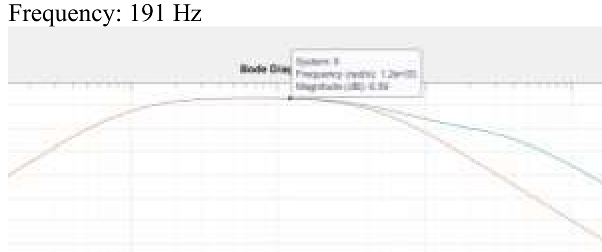
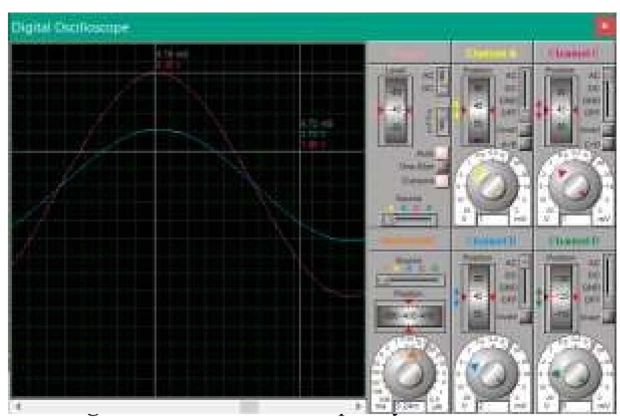


Figure 20. Simulation Frequency: 118 Hz.

Frequency: 191 Hz





Frequency: 422 Hz

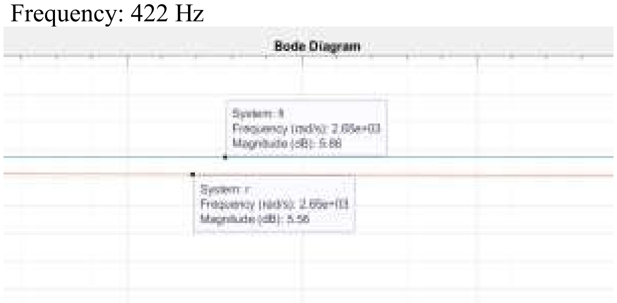


Figure 23. Bode diagram Frequency: 422 Hz

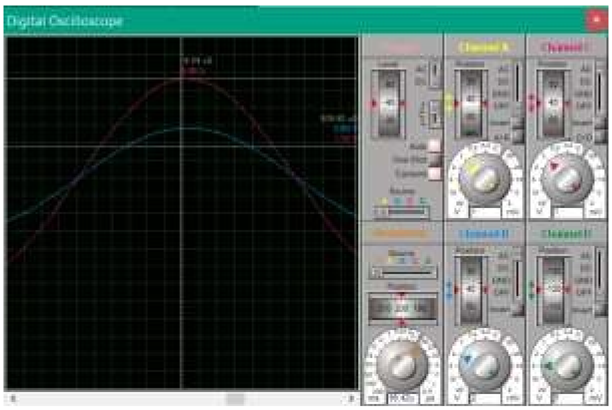
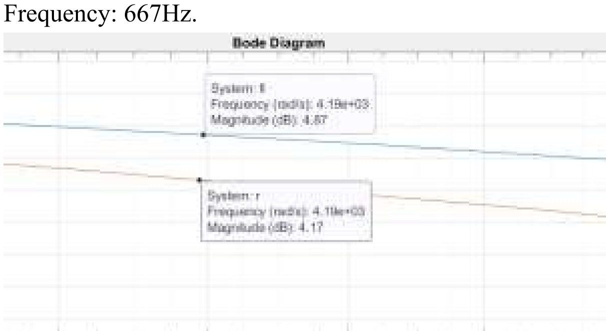


Figure 24. Simulation Frequency: 422 Hz

Frequency: 667Hz.



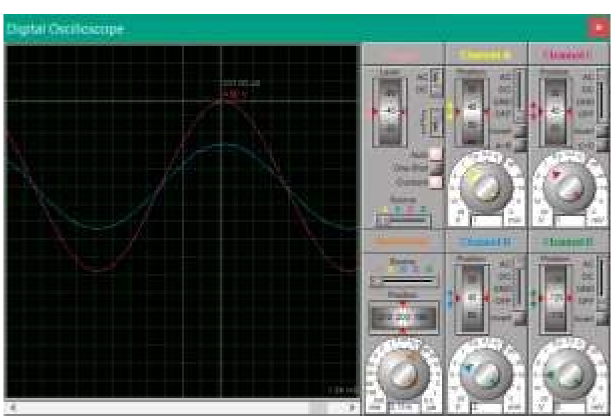


Figure 26. Simulation Frequency: 667 Hz

Frequency: 937 Hz

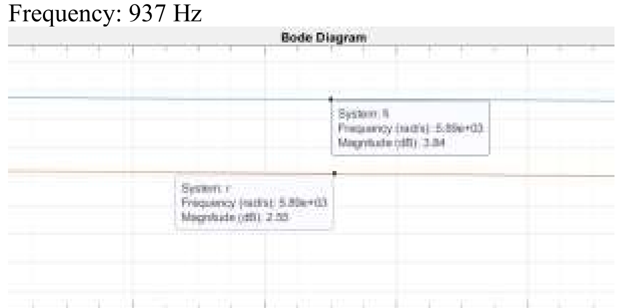


Figure 27. Bode diagram Frequency: 937 Hz

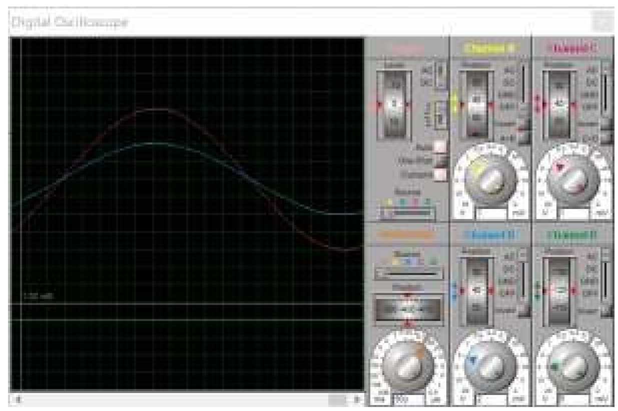


Figure 28. Simulation Frequency: 937 Hz

DISCUSSION AND ANALYSIS OF RESULTS

Table 1 shows the data obtained from the initial system, Table 2 shows the data from the compensated system.

Table 1. Plant data.

Frequency (Hz)	Gain (dB)	Ideal output voltage (V)	Actual output voltage (V)
118	6.66	6.45	6.4
191	6.59	6.39	6.30
422	5.56	5.69	5.65
667	4.17	4.84	4.8
937	3.84	4.66	4.0

Table 2. Compensated system data.

Frequency (Hz)	Gain (dB)	Ideal output voltage (V)	Actual output voltage (V)
118	6.66	6.45	6.40
191	6.59	6.39	6.35
422	5.86	5.89	5.70
667	4.87	5.25	4.88
937	2.55	4.02	4.0

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The realization of compensators in advance in frequency is applied to different systems in order to improve their response both in frequency and step, as can be seen in (Orlando, S.V.) where the design of a compensator in advance is appreciated, but applied to a dc motor, in which the improvement of the step response is observed by improving its displacement. Also in (Quintero, 2020) a control module is designed in advance-delay as a learning tool in control theory, which describes in detail each of the steps necessary for the creation of a compensator in advance and delay checking the functionality of this. In another research (Sanchez, 2024) you can see the design of a compensator in advance which applies to the modification of the characteristic times, ie the settling time, the peak time, the maximum over impulse and lifting time, these times are crucial to improve the behavior to the step response.

CONCLUSIONS

A band pass filter is a combination of a low pass and a high pass filter. It is very useful when we need to work with specific frequencies and eliminate the rest. In such a filter there are 3 important parameters to consider: the center frequency and the corner frequencies.

To modify our initial system, compensation can be used. In this project a forward compensation was performed. This is useful when we need to improve the stability of our system and advance the degree of dephasing of our output with respect to the input. There are other methods to perform the compensation, but in this case frequency analysis was used. With the help of Bode diagrams, a new phase margin was chosen and from that the other parameters and component values of the compensator were calculated.

As a future work, we will perform the forward-retard compensation and associate it with Python in which the corner frequencies will be modified. Another research that is underway is to add feedback to the circuit of this research considering an inverting adder with the CIUA741.

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ISSN: 2594 - 2905

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