ISSN: 2594 - 2905

Feedforward compensator for a transistorized AM modulator with frequency analysis
Lead compensator for a transistorized AM modulator with frequency analysis

López López Elí Azael[1], Sosa Cruz Pablo Moisés[2], Sanchez Santiago Pedro[3], Caballero Julián Franco Gabriel[4], Hernández Sánchez César[5]

https://doi.org/10.61117/ipsumtec.v8i1.365

[1]21160374@itoaxaca.edu.mx, orcid ID 0009-0006-4973-3100, Tecnológico Nacional de México/IT de Oaxaca
[2]21160406@itoaxaca.edu.mx, orcid ID 0009-0007-3907-7020, Tecnológico Nacional de México/IT de Oaxaca
[3]pedro.sanchez@itoaxaca.edu.mx, orcid ID 0009-0005-7223-0280, Tecnológico Nacional de México/IT de Oaxaca
[4]franco.caballero@itoaxaca.edu.mx, orcid ID 0000-0002-5024-7759, Tecnológico Nacional de México/IT de Oaxaca
[5]cesar.hernandez@itoaxaca.edu.mx, orcid ID 0009-0002-2890-8099, Tecnológico Nacional de México/IT de Oaxaca

Abstract -- This paper addresses the development and design of a feedforward compensator applied to an AM modulator to improve the stability and transient response, and optimizes the system performance by minimizing the over oscillation and improving the response speed, in addition, it allows to increase the transmission bandwidth.

Keywords: Frequency analysis, Compensator, AM modulator.

Abstract -- This document focuses on the development and design of a lead compensator applied to an AM Modulator with the aim of enhancing its stability and transient response. Furthermore, it seeks to optimize the system's performance by minimizing overshoot and improving response speed.

Key words -Frequency analysis, Compensator, AM modulator.

Introduction

In this report, the application of a feedforward compensator in an amplitude modulator (AM) is addressed with the objective of improving the stability and frequency response of the system. The context of study focuses on the challenges associated with the presence of certain phase lags in the AM signal, which can negatively affect its quality and efficiency. To address this issue, the implementation of a feedforward compensator is explored, highlighting its ability to introduce positive phase into the frequency response of the system. This approach translates into tangible benefits, such as improved frequency selectivity and minimized harmonic distortion, thus improving the overall quality of AM modulation. This report provides a detailed overview of the theory, design and results associated with the application of a feedforward compensator in a specific AM modulator context with frequency analysis.

Problem statement

Electrical control theory is essential in electronic engineering, especially in the design and analysis of control systems to regulate the behavior of electrical systems.

There are several researches on analog forward and backward compensators, such as the studies of Milocco [1] and Quintero et al [2] applied to different closed-loop systems. However, this study is distinguished by applying it to an AM modulator in frequency analysis. Its objective is to improve the behavior of the modulated signal, seeking to increase the stability and transient response of the system.

The main challenge lies in developing effective tools to improve the stability and performance of the modulating signal through control techniques. One of these techniques is the application of feedforward compensators, devices that modify the system response as a function of frequency to improve its stability and response speed.

According to Franklin et al [3], feedforward and lag compensators are still used in the control of various real systems, making them an essential topic in control education.

Justification

- **Understanding of feedforward compensators:** Feedforward compensators are fundamental components in the design of control systems. By applying them to a modulator, students can understand how these compensators can improve system stability and performance.
- **Importance of AM modulation:** Amplitude modulation (AM) is a fundamental technique in telecommunications, widely used in the transmission of audio and data signals. Improving its stability and quality is crucial to ensure effective communication.

Target

Build a feedforward compensator through frequency analysis with Bode diagrams applied to an AM Modulator, which will increase the gain and phase margin in addition to the minimization of the over oscillation, consequently, the overall stability of the system.

Scope

This project, being didactic, is directed to the students and teachers of electronic engineering of the Technological Institute of Oaxaca who are studying the subject of control II.

Limits

Availability of specialized tools to observe the behavior of the electrical signals produced by the compensator.

Limited to laboratory tests with sinusoidal and square signals.

Specific Objectives

- Perform the relevant calculations for the development of the compensator according to the characteristics required to modify the behavior of the Modulator.
- Analyze the experimental results of the compensator operation and, if necessary, adjust the parameters to optimize its performance.
- Implement the designed compensator in a physical prototype of the Modulator and perform experimental tests to verify its effectiveness in improving the gain margin and stability of the system.
- Adequately document the process of design, implementation and testing of the compensator in advance.

Theoretical Framework

Background of electrical compensators

Forward compensators are essential tools in the control of dynamic systems, designed to improve stability and transient response. They are based on adding forward phase in the frequency response of the system to counteract delays and increase the phase margin, which reduces unwanted oscillations. Its design involves carefully selecting the cutoff frequency and the amount of phase to add by frequency analysis as the Bode diagram. They are widely used in control, electronics and communications systems, especially when seeking to improve stability and dynamic response without introducing excessive damping.

Importance of compensator design

The importance of using a feedforward compensator lies in its ability to improve the stability and dynamic response of a control system. These devices increase the phase margin of the system, accelerate transient response, reduce unwanted oscillations and improve performance in closed-loop systems. In addition, they enable a more efficient design by achieving performance requirements with fewer components. In summary, feedforward compensators are crucial to ensure the stability and efficiency of control systems**.**

AM modulation

Amplitude modulation (AM) is a telecommunications technique where the amplitude of a carrier wave is adjusted according to the input signal to be transmitted. This modulating signal carries the information to be sent, such as voice or data. At the receiving end, the signal is demodulated to recover the original information. Although simple, AM is susceptible to noise and interference, limiting its use in applications requiring high signal quality.

It is common in broadcasting audio signals, such as AM radio stations.

Bode diagram

The Bode plot is an essential tool in engineering for analyzing the amplitude and phase response of a system as a function of frequency. It consists of two plots: one showing the gain of the system on a logarithmic scale and the other showing the phase shift of the output with respect to the input as a function of frequency. These plots are crucial for understanding how a system responds to different frequencies and for designing solutions such as compensators. They allow you to identify stability problems and delays that need correction in control and electronic systems.

Considerations for compensator design

When designing an advance compensator, it is essential to consider the following:

- Phase margin and gain: Make sure to increase the phase margin without affecting the gain at the frequency of interest.
- Crossover frequency: Introduce sufficient forward phase in the crossover frequency to improve stability.
- Type of compensator: Choose between different types according to system requirements and desired response.
- Signal amplitude: Design to handle signal amplitude without distortion.
- Practical implementation: Consider component availability and design complexity for successful implementation.

Types of compensators

- **Advance**

  A feedforward compensator is a device used in control systems to improve stability and transient response. It introduces forward phase into the frequency response of the system, increasing the phase margin and improving stability. Its design involves adjusting parameters such as crossover frequency and the amount of phase advance. In short, it helps to maintain system stability and reduce unwanted oscillations.

- **Delay**
  A lag compensator, or phase lag compensator, is a device used in control systems to improve system stability and performance. It introduces a delayed phase into the frequency response of the system, which helps to decrease the phase margin and improve stability. Its design involves adjusting parameters such as crossover frequency and the amount of phase lag. In short, it helps improve system stability and reduce overcompensation.

- **Adelanto-Retardo**
  A lead-lag compensator, also known as a phase-ahead-delay compensator, is a device used in control systems to improve stability and transient response. It combines characteristics of both leading and lagging compensators, introducing both leading and lagging phase into the frequency response of the system. This allows both the phase margin and the response speed of the system to be adjusted more precisely. Its design involves adjusting parameters such as the crossover frequency and the amount of leading and lagging phase. In summary, this type of compensator offers greater flexibility in system control, optimizing both stability and transient response.

DEVELOPMENT

Materials:

- 8 LM741 operational amplifiers
- 9 Resistors of 10kΩ
- 7 Resistors of 100kΩ
- 2 900Ω resistors
- 3 20kΩ resistor
- 3 1kΩ resistor
- 1 Resistors of 470Ω
- 1 Resistors of 5.1kΩ
- 1 1uF electrolytic capacitors
- 1 Ceramic capacitors of 100nF
- 3 10nF ceramic capacitor
- 1 1nF ceramic capacitor
- 1 Transistor 2N2222A
- 1 ESP-32 Microcontroller

AM modulation circuit assignment

This circuit was assigned by the professor where we were given the construction specifications of the circuit which consists of a transistor, resistors and capacitors. We were assigned this configuration with the purpose of obtaining a specific transfer function, where the input is the modulating signal and the output is the demodulated signal, in order to analyze how a 500 kHz carrier signal affects the input signal in relation to phase and amplitude. Figure 1 shows the circuit realized

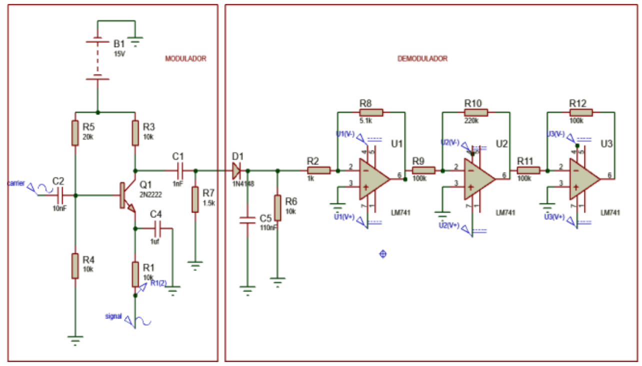


Figure. Assigned circuit.

Obtaining the AM Modulator circuit transfer function

To obtain the transfer function it was necessary to perform it through an experimental method, in which an input signal was entered with different frequencies from the order of Hertz to Kilo Hertz, its amplitude was measured in decibels and its phase in degrees using a digital oscilloscope, so that each input frequency corresponds to two output data. However, to obtain the transfer function, the frequencies in radians per second are needed, so Python was the tool used to process these conversions and then plot the data.

```python
amplitud = [6.44,6.44,6.44,6.44,6.44,6.44,6.44,6.44,6.44,
            6.44,6.44,6.3,6.3,6.3,5.87,5.57,5.26,5.1,4.77,
            4.43,1.33,-1.58,-4.43,-7.39,-9.89,-12.39,-14.57,
            -16.28,-18.17,-29.54,-32.64,-32.64,-32.64,-32.64,
            -32.64,-32.64,-32.64,-32.64]
frecuencia = [1,10,20,30,40,50,60,70,80,90,100,200,300,400,
              500,600,700,800,900,1000,2000,3000,4000,5000,
              6000,7000,8000,9000,10000,20000,30000,40000,
              50000,60000,70000,80000,90000,100000]
fase=[0,0,0,0,0,0,0,0,0,0,0,-11,-23,-25.92,-28.8,-34.56,-37.8,
      -40.32,-48.6,-50.4,-83.52,-103.68,-138.24,
      -154.8,-172.8,-176.4,-201,-201,-208.9,-208.9,
      -208.9,-208.9,-208.9,-208.9,-208.9,-208.9,-208.9,-208.9]
radianes=[]

for i in (frecuencia):
    radianes.append(i/(2*math.pi))#pasamosde Hz a rad/seg
```

Figure. Data analysis with python.

With the data obtained experimentally, asymptotes were proposed which, when added together, result in a graph that approximates the real results.

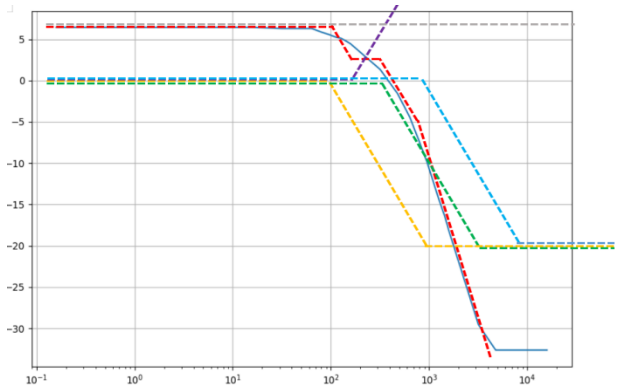


Figure. Proposed asymptotes.

Knowing the cut-off frequencies of the proposed asymptotes, it is possible to obtain the equation in the Laplace domain of each of the components.

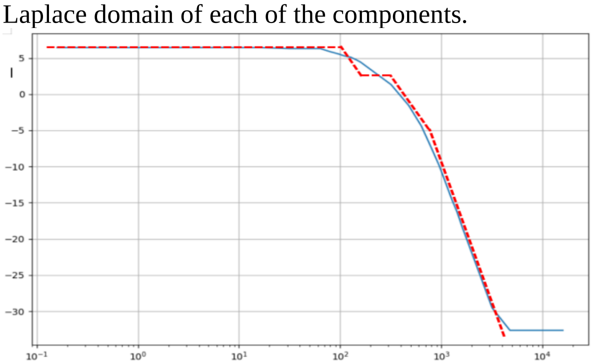


Figure. Resulting graph from the proposed asymptotes.

The final transfer function contains three poles and a zero.

$$G(s) = \frac{2.1\left(1+\frac{s}{6283}\right)}{\left(1+\frac{s}{5026}\right)\left(1+\frac{s}{12566}\right)\left(1+\frac{s}{32044}\right)} \qquad \text{Eq. (1)}$$

Bode plot of the system

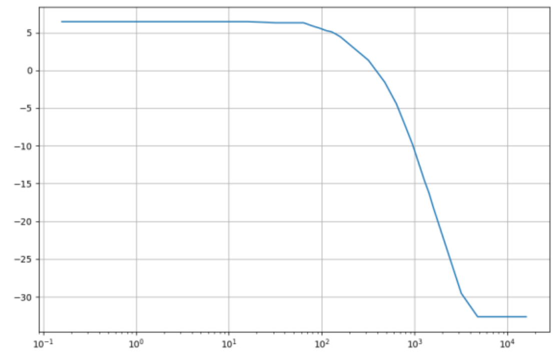
Once the transfer function of the AM modulation system was obtained, we proceeded to obtain its respective Bode diagram, using Matlab software where the data describing the transfer function was entered, Figure 2 shows the code entered in Matlab.

```
s = tf ('s')
f = (1*2.1*(1+(s/6283)))/((1+(s/5026.39))*(1+(s/12554.13))*(1+(s/32044.24))
figure(1)
margin(f)
```

Figure 5. Code to obtain the Bode plot

- Bode diagram obtained experimentally.

Figure. Bode diagram of the circuit with experimental data.



- Bode diagram in Matlab

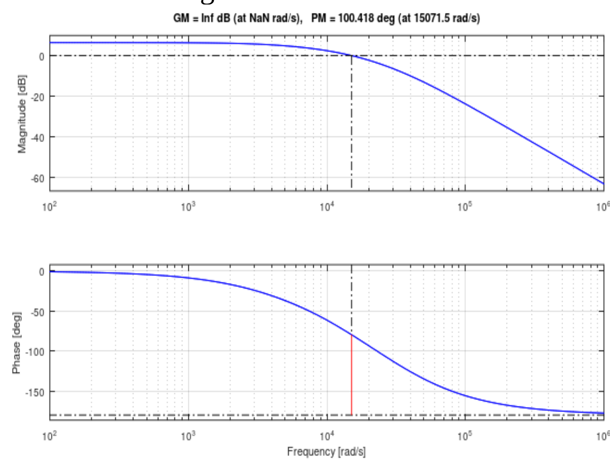


Figure. Bode diagram obtained in Matlab.

After obtaining the graph using Matlab, we proceeded to compare it with the data obtained through the experimental method. The purpose of this comparison was to verify if both graphs coincided and thus verify that the one obtained experimentally was correct since it governs the transfer function of the system, once verified we proceeded to make the compensator.

Forward compensator design.

To design the compensator, the steps described in the book "Modern Control Engineering" by Ogata, 5th edition [4] were followed. The book states that the main function of the feedforward compensator is to adjust the frequency response to provide a forward phase angle necessary to counteract the excessive phase delay inherent in the system components.

The steps are as follows:

1. The equation describing the forward compensator is given which is:

$$G(S) = K\frac{Ts+1}{\alpha Ts+1} \qquad \text{Eq. (2)}$$

Where we first had to find the value of the gain K that satisfies the requirement on the static error constant proposed by us which was Kv =

ISSN: 2594 - 2905

$3765.71\, seg^{-1}$. The following equation was used to find K

$$\lim_{s\to 0} s\, G_c(S)G(s) = \lim_{s\to 0} s\, K\, \frac{Ts+1}{\alpha Ts+1} \qquad \text{Eq. (3)}$$

Substituting the equation we obtain:

$$3765.71 = \lim_{s\to 0} s\, K \frac{2.1\left(1+\frac{s}{6283}\right)}{\left(1+\frac{s}{5026}\right)\left(1+\frac{s}{12566}\right)\left(1+\frac{s}{32044}\right)} \qquad \text{Eq. (4)}$$

When evaluating the limit, we encountered an indeterminacy, so we resorted to L'Hôpital's rule. This rule allowed us to obtain the value of the gain K , leaving

K = 3.49

2. Once the value of the gain K was obtained, the next step was to make the Bode diagram by multiplying the gain K obtained by the transfer function of the system. The Bode diagram was obtained in Matlab with the following code.

```
s = tf ('s')
f1 = (3.49*2.1*(1+(s/6283)))/((1+(s/5026.39))*(1+(s/12554.13))*(1+(s/32044.24))

figure(1)
margin(f)
```

Figure. Matlab code to obtain the Bode diagram with K gain.

The resulting Bode diagram is as follows:

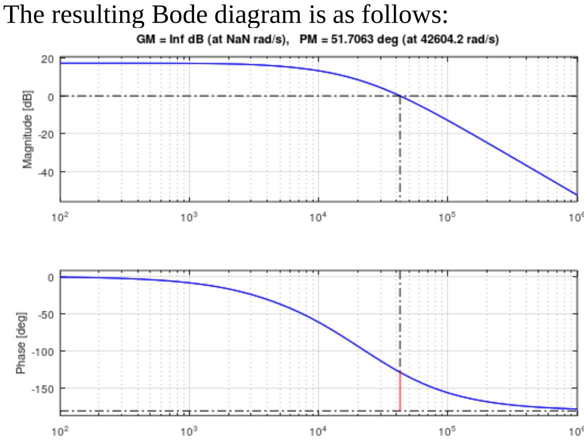


Figure 9. Bode diagram with the gain K

3. The third step was to add an additional phase from 5° to 12°, this range is established in the Modern Control Engineering book by the author K. Ogata, so in our case it was 12°.

$$\emptyset m = 70° - 51.7° + 12° = 30.3° \qquad \text{Eq. (5)}$$

4. The next step was to determine the attenuation factor α which we calculated with the following equation.

$$\alpha = \frac{1-\sin \emptyset m}{1+\sin \emptyset m} \qquad \text{Eq. (6)}$$

$$\alpha = \frac{1-\sin 30.3°}{1+\sin 30.3°} = 0.329 \qquad \text{Eq. (7)}$$

Once we calculated this value we chose a new gain crossover frequency which was obtained with the following formula:

$$\omega_c = \frac{1}{\sqrt{\alpha}} = \frac{1}{\sqrt{0.329}} = 1.743 \qquad \text{Eq. (8)}$$

$$1.743\ dB \cong 4.83\ rad/s$$

5. The next step was to set the new corner frequencies of the forward compensator as follows:

$$\text{Zero } \frac{1}{T} = \sqrt{\alpha}\omega_C = 33787.6 \qquad \text{Eq. (9)}$$

$$\text{Polo} \frac{1}{\alpha T} = \frac{\omega_C}{\sqrt{\alpha}} = 109965.76 \qquad \text{Eq. (10)}$$

6. The next step was to determine the gain Kc which we did as follows:

$$K_c = \frac{K}{\alpha} = \frac{3.49}{0.329} = 11.39 \qquad \text{Eq. (11)}$$

7. The last step is to verify that the profit margin is satisfactory, we check this with the Bode plot of the transfer function multiplied by the compensator function multiplied by Kc as dictated by the following equation.

$$K_c G_c(S)G(s) = (11.39)\left(\frac{s+33787.6}{s+109965.76}\right)\left(\frac{2.1\left(1+\frac{s}{6283}\right)}{\left(1+\frac{s}{5026}\right)\left(1+\frac{s}{12566}\right)\left(1+\frac{s}{32044}\right)}\right) \qquad \text{Eq. (12)}$$

Once the transfer function of the compensated system was obtained, its Bode diagram was made to verify the result, which was as follows

EDUCACIÓN | TECNOLÓGICO NACIONAL DE MÉXICO | IPSUMTEC
ISSN: 2594 - 2905

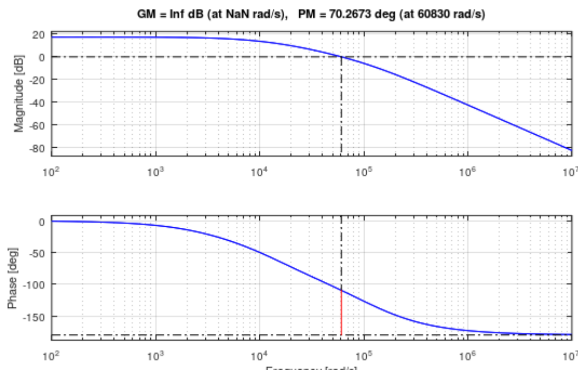


Figure 10. Bode diagram of the Compensated system.

As shown in Figure 10, the phase margin corresponds to the 70° we wanted to obtain, so it was verified that the compensator was correct and therefore the system as well.

Compensator components

$$Gc(s) = Kc \cdot \left(\frac{s + \frac{1}{T}}{s + \frac{1}{\alpha T}} \right) \qquad \text{Eq. (13)}$$

$$Gc(s) = \frac{R_4 C_1}{R_3 C_2} \cdot \left(\frac{s + \frac{1}{R_1 C_1}}{s + \frac{1}{R_2 C_2}} \right) \qquad \text{Eq. (14)}$$

Like

$$Gc(s) = 11.39 \cdot \frac{s + 33787.6}{s + 109965.76} \qquad \text{Eq. (15)}$$

To obtain the equivalent values of the circuit components for the compensator, the values of C_1= 1nF, C_2= 10nF and R_4= 100kΩ were proposed, so using equation 14, the following values were obtained

$$R_1 = 29.64\ K\Omega$$
$$R_2 = 909.3\ \Omega$$
$$R_3 = 877.9\ \Omega$$

DISCUSSION AND ANALYSIS OF RESULTS

Prior to the analysis of the results, it is important to highlight the methods used in the development of this work and compare them with other research in order to know different points of view and considerations that were not taken into account in this work, as well as to highlight the findings of this research.

For the AM modulator-demodulator part, using a circuit based on a transistor and diode circuit as a signal multiplier, the mathematical analysis and modeling of the transfer function was complicated, so the experimental method was the best option to model its behavior only with respect to the modulating signal. However, mathematical analysis of circuits with active components already exists [5].

In the work of Flores et al. [6] they use the AD633 analog multiplier as modulator. This integrated circuit has the advantage of providing in its data sheet the transfrence function with respect to its inputs. In addition, they use a colpitts oscillator as the generator of the carrier signal, unlike our work which uses the DAC of an ESP32 to generate a 500kHz signal, which is not completely analog. This may imply different behaviors of the system compared to a signal generated by an analog oscillator.

On the other hand, there are different ways to design a feedforward compensator, in this case it was decided to use the phase margin criterion when working with a frequency analysis. In this way, the values of the compensator can be adjusted according to the desired phase margin, extending the frequency range accepted by the system. However, for systems focusing on the response in the time domain there is the geometric root locus method [7].

After designing the compensator, the circuit was tested following the schematic in Figure 11.

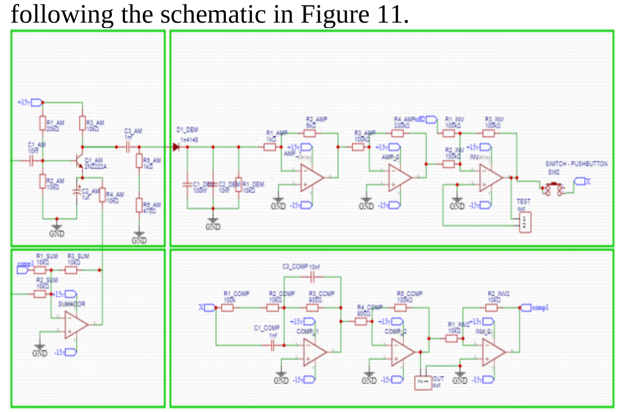


Figure. Circuit with compensator.

The next step, naturally, is the implementation of the circuit (compensated) once the times and values of the compensator have been checked, as these must be equal to those calculated.

Figure 12 shows an amplitude of 7v at the output, with respect to the 6v input, it is determined that the uncompensated circuit has a gain of 1.3 dB at a frequency of 2 kHz, equivalent to 12,566 rad/s. This response coincides with the graph in Figure 7.

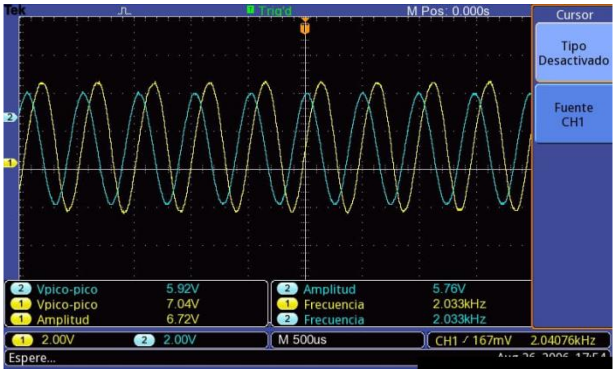


Figure. Signal of the circuit with 2Khz compensator.

The response of the circuit with the compensator is shown in Figure 13. At a frequency of 3kHz there is a gain of 11.7 dB, which coincides with the graphs calculated in the compensator part.

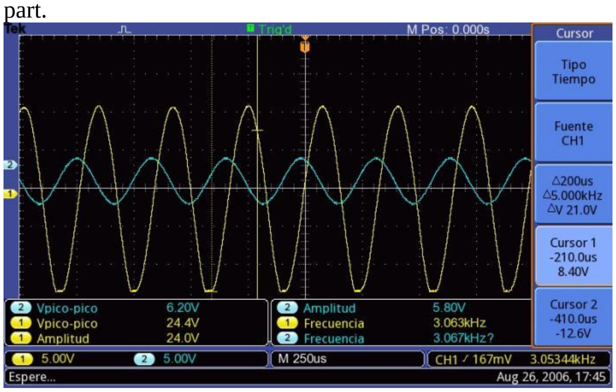


Figure. Signal of the circuit with compensator 3Khz.

After testing the circuit on the breadboard, the next action to be taken was to design a PCB containing the entire circuit, for which the EasyEDA software was used and the design is shown in Figure 14.

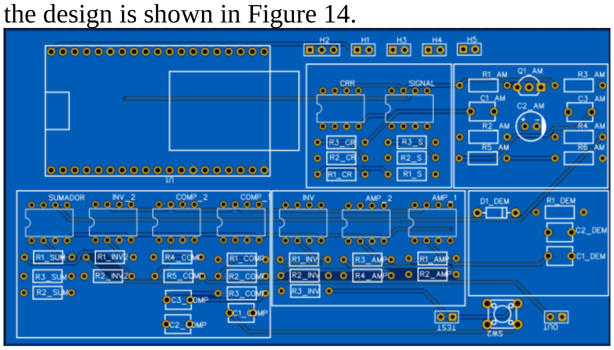


Figure. PCB of the circuit with the compensator.

Finally, the final step was to solder the components to the PCB and perform some final tests to verify that all the components had been placed correctly and that the circuit together with the compensator did not present variations to the results obtained previously.

Figure. PCB completed.

The amplitude of the compensated signal corresponds to those shown in Figs. 12 and 13 at their respective frequencies, and the phase angle between the input signal (the message or modulating signal) and the compensated output signal was also checked.

The phase angle was checked after obtaining the time difference between the two signals T_{12}= 35us and with that data the following equation was applied.

$$\emptyset = T_{12} \cdot f \cdot 360° \qquad \text{Eq. (16)}$$

$$\emptyset \approx 35 \cdot 10^{-6}s \cdot 9500hz \cdot 360° \qquad \text{Eq. (17)}$$

$$\emptyset \approx 119° \qquad \text{Eq. (18)}$$

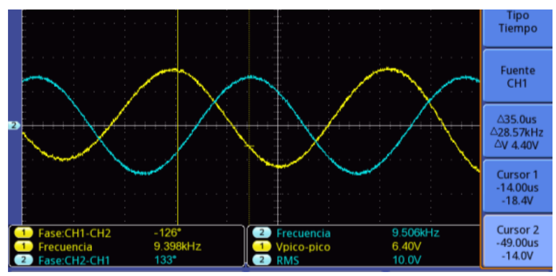


Figure. Phase shifts between input (yellow) and output (blue) signals at 9.5Khz.

It was also checked with another frequency, this time at 2.3Khz, where the time difference between both signals is T_{12}= 100us, then.

$$\emptyset = T_{12} \cdot f \cdot 360° \qquad \text{Eq. (19)}$$

$$\emptyset \approx 100 \cdot 10^{-6}s \cdot 2300hz \cdot 360° \qquad \text{Eq. (20)}$$

$$\emptyset \approx 83° \qquad \text{Eq. (21)}$$

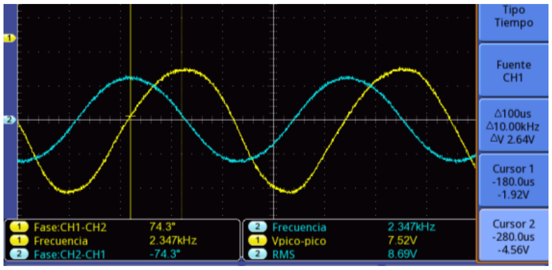


Figure. Phase shifts between input (yellow) and output (blue) signals at 2.3Khz.

These phase shifts and amplitudes correspond to the results obtained in matlab shown in Fig. 10.

CONCLUSIONS

In conclusion, this study has explored the implementation of a compensator specifically designed to improve the phase and gain margin of an AM modulator in frequency analysis with Bode diagrams.

This approach offers significant practical applications in fields such as telecommunications and electronics. For example, in data and voice transmission systems, the implementation of compensators can improve signal quality, reducing unwanted response times and minimizing signal distortion.

Furthermore, in the field of communications engineering, the application of compensators in AM modulators helps to optimize the transient response of transmission systems, improving the efficiency and reliability of communications.

This study not only provides a detailed analysis of the application of compensators in a specific AM modulator context in frequency analysis, but also demonstrates the practical utility of these devices in modifying and improving the response of communication systems, with benefits in several areas of technology and engineering.

For future research we intend to analyze in more detail the behavior of the transistor from a mathematical point of view to obtain an accurate transfer function that allows a more precise adjustment of the phase margin and compare it with the experimental method to determine the magnitude of the errors that the latter can give us.

Likewise, investigating the AD633 multiplier in conjunction with a diode-based demodulator can be an excellent option to study the demodulator behavior in isolation, considering that the modulator circuit is ideal and does not provide attenuation or phase shift of the signals.

ACKNOWLEDGMENTS

We thank the Instituto Tecnológico de Oaxaca and the Department of Electronic Engineering for the loan of the laboratory and equipment for this project.

BIBLIOGRAPHY .

[1] Milocco RH. Design of a feedforward compensator for power-frequency control in hydraulic turbines for power generation [Internet]. [Quito]: Escuela Politécnica Nacional; 1989 [cited Mar 11, 2025]. Available from: https://bibdigital.epn.edu.ec/handle/15000/9557

[2] Quintero-Rojas J, CB, Coronel M. Design and construction of an analog control module type forward-retarder as a learning tool in control theory [Internet]. Rev Téc Fac Ing Univ Zulia. 2020;43(3):150-8. Available at: https://www.redalyc.org/articulo.oa?id=605766264006

[3] Franklin GF, Powell JD, Emami-Naeini A. Feedback control of dynamic systems. 8th ed. Boston: Pearson; 2014.

[4] Ogata K. Modern control engineering. 5th ed. Madrid: Pearson Educación; 2010.

[5] Baratchart L, Chevillard S, Seyfert F. On transfer functions realizable with active electronic components [Research Report]. INRIA; 2014. Available from: https://inria.hal.science/hal-01098616/

[6] Francisco FC. Design of an AM modulator-demodulator [Doctoral thesis on the Internet]. [Mexico]: Instituto Politécnico Nacional; 2018. Available from: https://tesis.ipn.mx/bitstream/handle/123456789/27651/Tesis.pdf?sequence=1&isAllowed=y

[7] Nica EO. Design of a PID controller by geometric root locus analysis for a levitation system [Internet]. [Mexico]: Instituto Politécnico Nacional; Available from: https://tesis.ipn.mx/bitstream/handle/123456789/5522/ice13.pdf?sequence=1.

[8] Diarioelectronicohoy. The operational amplifier [Internet]. 2002 [cited 2023 Dec 2]. Available from: https://www.diarioelectronicohoy.com/blog/el-amplificador-operacional

[9] Kuo BC, Golnaraghi F. Automatic control systems. 10th ed. New York: McGraw-Hill; 2017.

[10] Nilsson JW, Riedel SA. Electric circuits. 10th ed. Boston: Pearson; 2015.

[11] Boylestad RL, Nashelsky L. Electronics: theory of circuits and electronic devices. Mexico City: Pearson Educación; 2003.

[12] Floyd TL, Salas RN, Gonzalez LMO, Lopez GP. Principles of electrical circuits. Mexico City: Pearson Educación; 2007.

[13] Floyd TL. Electronic devices. Mexico City: Limusa; 2002.

[14] Technical Journal of the Faculty of Engineering, University of Zulia. Design and construction of an analog control module type forward-retarder as a learning tool in control theory [Internet]. 2020;43(3):150-158. Available at: https://www.redalyc.org/articulo.oa?id=605766264006

[15] Ornelas F. Analog control II: Design and compensation of systems in the frequency domain [Internet]. Universidad Michoacana de San Nicolás de Hidalgo; [cited 2023 Dec 2]. Available from: https://dep.fie.umich.mx/~fornelas/data/uploads/pres_03_dc.pdf

[16] Alexander CK, Sadiku NO. Fundamentals of electric circuits. 4th ed. New York: McGraw-Hill; 2008.

[17] Sedra AS, Smith KC. Microelectronic circuits. 7th ed. Oxford: Oxford University Press; 2015.

[18] Dorf RC, Bishop RH. Modern control systems. 13th ed. Boston: Pearson; 2017.

[19] Haykin S, Van Veen B. Signals and systems. 2nd ed. Hoboken: John Wiley & Sons; 2007.

[20] Nise NS. Control systems engineering. 8th ed. Hoboken: Wiley; 2020.

CONTRIBUTION ROLES

Role	Authors

Conceptualization	Elí Azael López López (Principal) Pablo Moisés Sosa cruz (Contributor)
Data Curation	Pablo Moises Sosa cruz
Methodology	Elí Azael López López (principal) Pablo Moisés Sosa cruz (same)
Project management	Pedro Sanchez Santiago
Resources	Elí Azael López López (principal) Pablo Moisés Sosa cruz (same)
Software	Elí Azael López López
Supervision	Franco Gabriel Caballero Julián
Validation	Franco Gabriel Caballero Julián
Visualization	Pedro Sanchez Santiago
Drafting (Original Draft)	Elí Azael López López (principal) Pablo Moisés Sosa cruz (support)
Writing (Proofreading and editing)	César Hernández Sánchez