AN EDUCATIONAL STUDY OF AMPLITUDE MODULATION CIRCUITS USING MATHEMATICAL MODELING AND LABORATORY EXPERIMENTS

MIHAELA ALDEA[1], DOBRA REMUS[2], FLORIN SAMOILA[3], GEORGETA BUICA[4]

Abstract: This paper presents a comprehensive analysis of an amplitude modulation (AM) circuit based on mathematical modeling, MATLAB-based simulation, and laboratory measurements. An analytical model of the AM modulation process is first developed to describe the circuit behavior under ideal and non-ideal operating conditions. The proposed model is then implemented in MATLAB to evaluate key performance characteristics, including modulation index, spectral components, and signal distortion. To validate the theoretical and simulation results, an experimental AM modulation circuit is implemented and tested in a laboratory environment. Measured results are compared with analytical predictions and simulation outcomes, demonstrating good agreement across different operating conditions. The combined use of mathematical analysis, simulation, and experimental validation provides a robust framework for understanding AM circuit performance and highlights the effectiveness of MATLAB-based tools in supporting circuit analysis and verification.

Key words: amplitude modulation (AM), signal spectrum analysis, experimental validation, analog communication systems.

1. ANALYSIS OF EDUCATIONAL APPROACHES TO AMPLITUDE MODULATION

Educational investigations of amplitude modulation commonly employ three methodological approaches: analytical modeling, simulation-based analysis, and laboratory experimentation. Each approach contributes distinct insights into AM

[1] Ph.D. Senior Lecturer, 1 Decembrie 1918 University of Alba Iulia, maldea@uab.ro

[2] Ph.D.Eng. Associate Professor, 1 Decembrie 1918 University of Alba Iulia, remusdobra@uab.ro

[3] Ph.D. Student, 1 Decembrie 1918 University of Alba Iulia, samoila.florin13@gmail.com

[4] Ph.D.Eng. , "Alexandru Darabont" National Research and Development Institute of Occupational Safety (INCDPM), Ghencea 35, 061692, Bucharest, Romania, gbuica@protectiamuncii.ro,

behavior; however, each is subject to specific constraints that influence its effectiveness and scope [1], [5], [8].

Analytical modeling enables the formal derivation of AM signal expressions and provides insight into spectral properties, modulation index behavior, and ideal system performance. This approach is essential for establishing a theoretical reference against which other methods may be evaluated. Essentially idealized assumptions are used to construct analytical models, which do not account for non-linearities, noise, or component tolerances. The method offers little information about the impact of implementation. When implemented without corrective modeling, quantitative findings may differ from real-world realizations [2], [9].

Simulation environments, such as MATLAB or Simulink, facilitate numerical evaluation of AM systems under controlled conditions. Parameter sensitivity analysis and frequency-domain inspection can be performed efficiently, enabling systematic investigation beyond analytical tractability. The accuracy of the underlying models sets a limit on simulation fidelity. If hardware-dependent events are not clearly modeled, numerical results may obscure them. An over-reliance on simulation could make it harder to critically assess real-world limitations.

Experimental investigation provides empirical validation of AM circuit behavior and captures non-ideal effects inherent in physical implementations. Measurement data enable direct assessment of discrepancies between theoretical predictions and actual system performance. Environmental variables and instrument accuracy may have an impact on experimental reproducibility. The range of possible operating circumstances is limited by hardware limitations. Measurement noise and setup variability might affect how data is interpreted.

Comparative analysis indicates that each approach addresses a distinct dimension of AM system characterization. Analytical modeling offers theoretical baselines, simulations enable parametric exploration, and experiments provide empirical validation. However, the independent application of any single approach yields an incomplete characterization of AM behavior. An integrated analytical–simulation–experimental methodology reduces methodological bias and enhances result reliability. By cross-validating outcomes across multiple domains, this combined framework supports a more rigorous and comprehensive evaluation of amplitude modulation systems in an educational context.

The circuit diagram from figure 1, shows the experimental and analytical framework used to implement and evaluate an amplitude modulation (AM) circuit based on an analog multiplier (AD633). The system is composed of three main functional stages: signal generation, modulation, and observation.

A low-frequency modulating signal is generated with a tunable frequency range of approximately 1 kHz to 50 kHz. This signal represents the baseband information to be transmitted. In parallel, a high-frequency carrier signal is generated with a frequency range between 200 kHz and 700 kHz, consistent with standard AM operation conditions [3], [7].

Both signals are applied to the input ports of the AD633 analog multiplier, which performs real-time signal multiplication. The AD633 internally scales the product of the input signals and provides a summed output stage, enabling the realization of

conventional amplitude modulation. By appropriate biasing and scaling, the output corresponds to a standard AM waveform in which the carrier amplitude is varied according to the modulating signal [4], [6].

The implementation is based on AD 633, analog multiplier (used for modulation/demodulation, phase detection, as voltage-controlled amplifier/attenuator/filter). The multiplier operates from dual-polarity power supplies ranging from ± 8 V to ± 18 V (inputs should stay within roughly ± 10 V to avoid clipping.) and with a nominal output voltage of 10 V full scale (provided by a buried Zener reference). For more detailed technical information, including pin configurations and performance characteristics, you can refer to the official AD633 datasheet (Analog Devices).
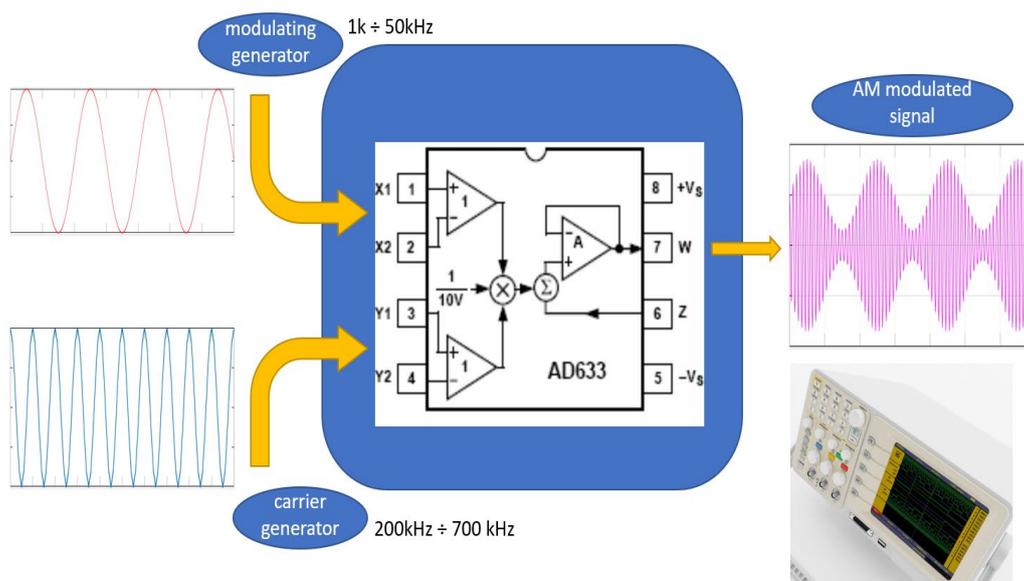

Fig.1. UML Block Diagram using SysML-style blocks, which is the correct UML family for engineering systems like protection relays of most common interdependencies

The AD633 is commonly used for AM modulation. It multiplies two analog input voltages and provides a scaled output: $W = (X+Y)/10 + Z$

For the duration of the whole exercise the panel B (AM modulation) has to be supplied with a modulating signal and carrier signal, by using cables of suitable length and of such color to make easier the control of the connections.

The resulting AM-modulated signal is observed at the output using laboratory measurement equipment (e.g., digital oscilloscope), allowing time-domain visualization of the modulated waveform and indirect verification of modulation depth, envelope shape, and signal integrity [10].

This schematic supports both analytical modeling and experimental validation, making it suitable for systematic comparison between theoretical predictions, MATLAB-based simulations, and physical measurements.

2. MATHEMATICAL MODEL OF THE AM MODULATION CIRCUIT

2.1 Mathematical Model implementation

The amplitude modulation process implemented in the proposed system is based on the multiplication of a low-frequency modulating signal with a high-frequency carrier signal using an analog multiplier (AD633).
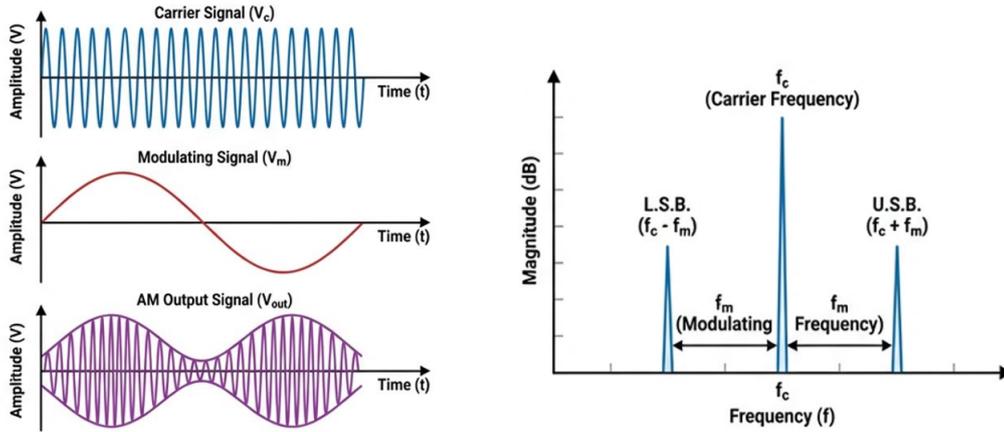

Fig.2. Experimental study of AM modulation: a) time domain waveforms; b) frequency spectrum

The modulating signal is modeled as a sinusoidal waveform:

$$m(t) = A_m cos(2\pi f_m t) \tag{1}$$

Where A_m is the amplitude of the modulating signal and f_m is the modulating frequency (1kHz, 50kHz).
The carrier signal is defined as:

$$c(t) = A_c cos(2\pi f_m t) \tag{2}$$

Where A_c is the carrier amplitude and f_m is the carrier frequency (200kHz,700kHz).
The AD633 performs analog multiplication according to the relationship:

$$v_0(t) = \frac{(x_1-x_2)(y_1-y_2)}{10} \tag{3}$$

the output voltage becomes:

$$v_0(t) = A_c[1 + \mu cos(2\pi f_m t)]cos(2\pi f_c t) \tag{4}$$

2.2. Modulation circuit analysis

This next figure illustrates a circuit for the Amplitude Modulator (AM) using a general-purpose analog multiplier integrated circuit (IC) such as the MC1496 or AD633.
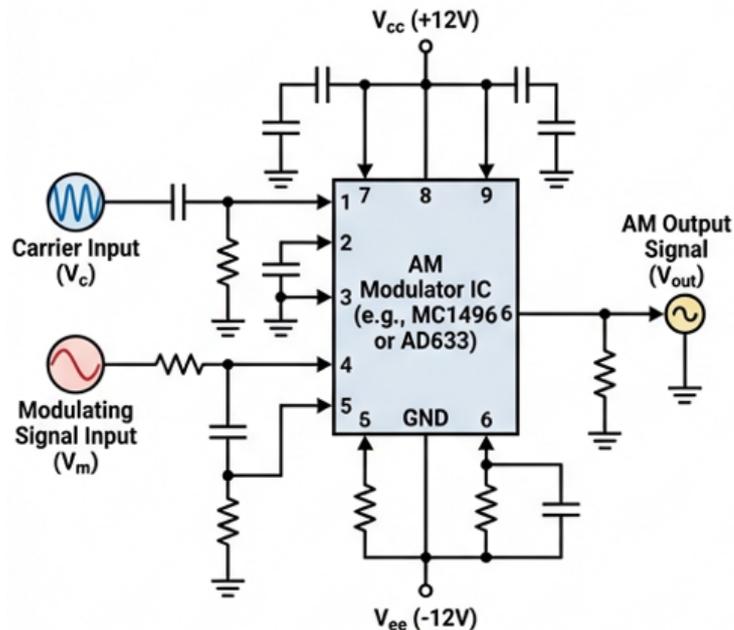

Fig.3. Experimental circuit diagram of the AM modulator

The amplitude modulation circuit's purpose is to combine a high-frequency carrier signal (Vc) with a lower-frequency modulating signal (Vm), which contains the information, e.g., audio) to produce an Amplitude Modulated (AM) output signal (Vout).

3. THE MODEL FOR EXPERIMENTAL ANALISYS OF THE AMPLITUDE MODULATION CIRCUIT

Figure 4 shows the effect of overmodulation on an AM (Amplitude Modulation) signal by displaying three separate time-domain waveforms, each corresponding to a different modulation index (m). The modulation index is the ratio of the amplitude of the modulating signal to the amplitude of the carrier signal. The amplitude of the high-frequency carrier wave varies in accordance with the lower-frequency modulating signal, but the carrier amplitude never reaches zero. The signal envelope (the outline of the peaks of the carrier wave) perfectly follows the shape of the original modulating signal without any distortion, ensuring high fidelity upon demodulation.

Overmodulation causes severe distortion of the signal, which results in a garbled or unintelligible message when received by a standard AM receiver. It also produces unwanted harmonics that can interfere with signals in adjacent frequency channels
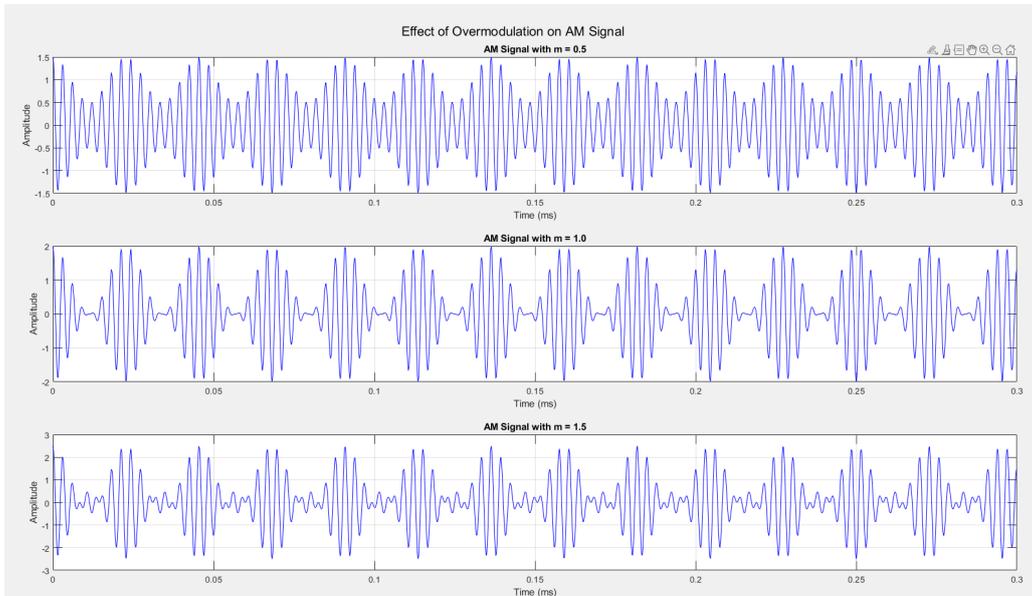
Fig.4. Matlab simulation of the effect of overmodulation on an AM (Amplitude Modulation) signal

The figure 5 shows two main components that combine to form the modulated signal. Blue Waveform (Carrier Signal): This is a high-frequency alternating current (AC) signal that spans the majority of the vertical range. Its fast oscillation serves as the basis upon which information is transmitted
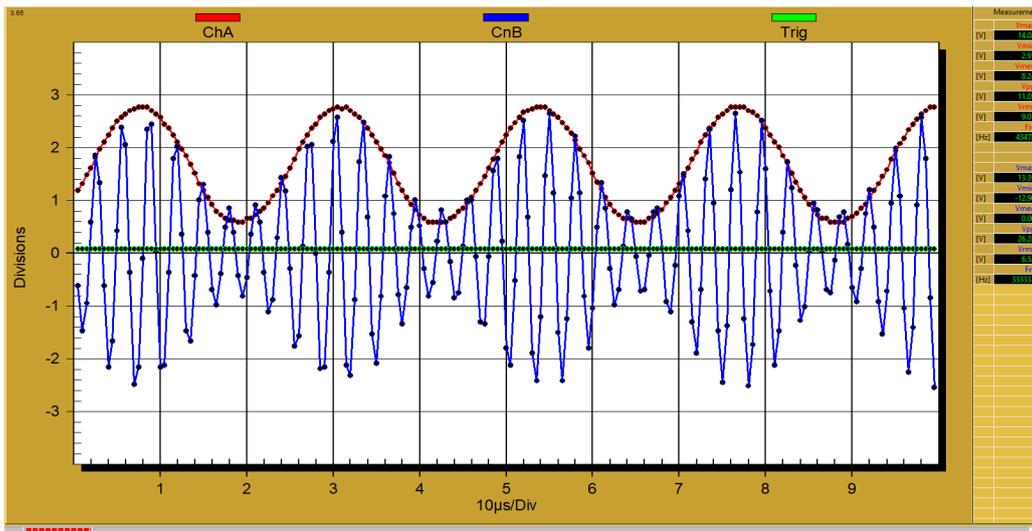

Fig.5. Acquisition software for measurement of AM signals waveforms

Red Waveform (Modulating Signal/Envelope): This is a lower-frequency signal that follows the peaks and troughs of the blue carrier wave. It is the information signal (e.g., an audio tone) that is being transmitted.

The next figure is a spectrum analyzer showing the frequency domain representation of an Amplitude Modulation (AM) signal. The graph displays the signal's amplitude in decibels (dB) on the vertical axis versus frequency in megahertz (MHz) on the horizontal axis.
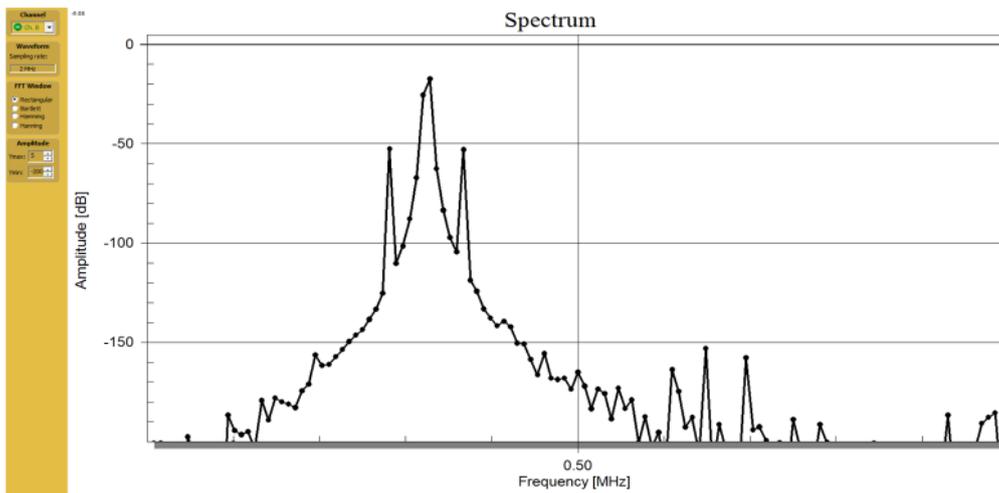

Fig.6. Acquisition software for measurement of AM signals waveforms
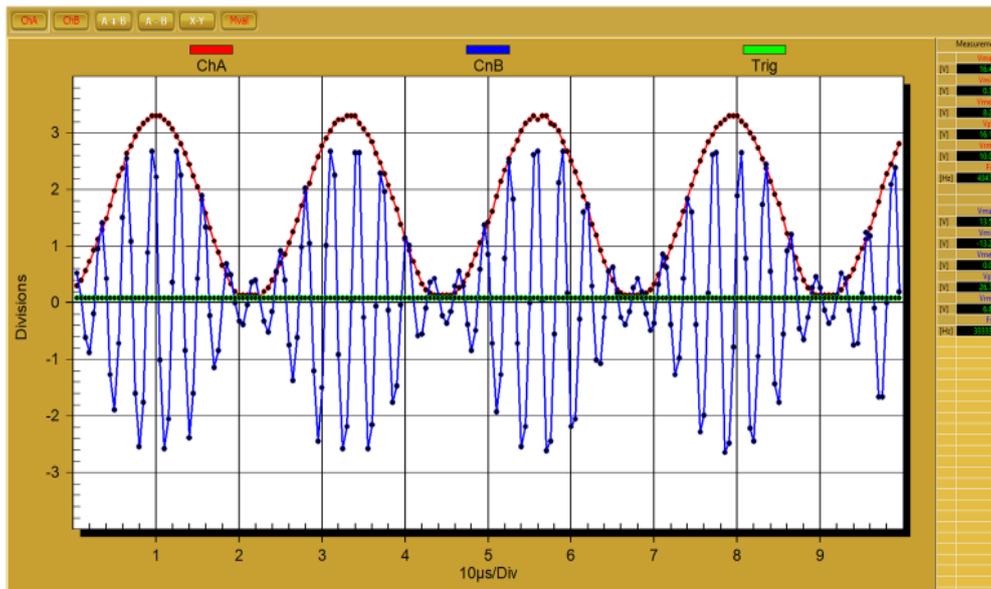

Fig.7. Acquisition software for measurement of AM signals waveforms

This display is crucial to analyze the spectral purity, power distribution, and modulation depth of a signal, ensuring it adheres to regulated bandwidths and minimizes interference with adjacent frequency channels.
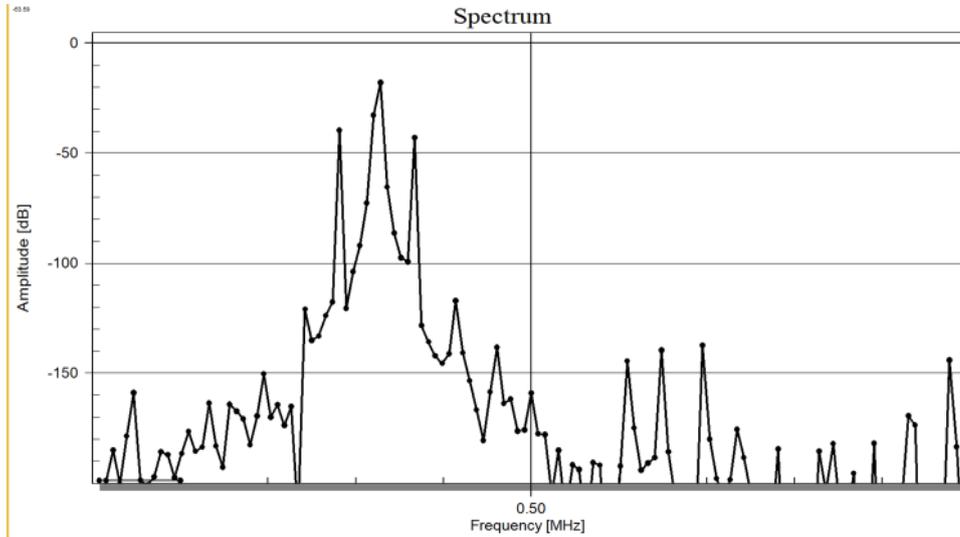
Fig.8. Acquisition software for measurement of AM signals waveforms

The specific pattern from figure 9 is characteristic of an Amplitude Modulation (AM) signal analysis using a trapezoidal method. The resulting waveform forms a distinctive trapezoidal pattern, also known as a Lissajous figure in an AM context.
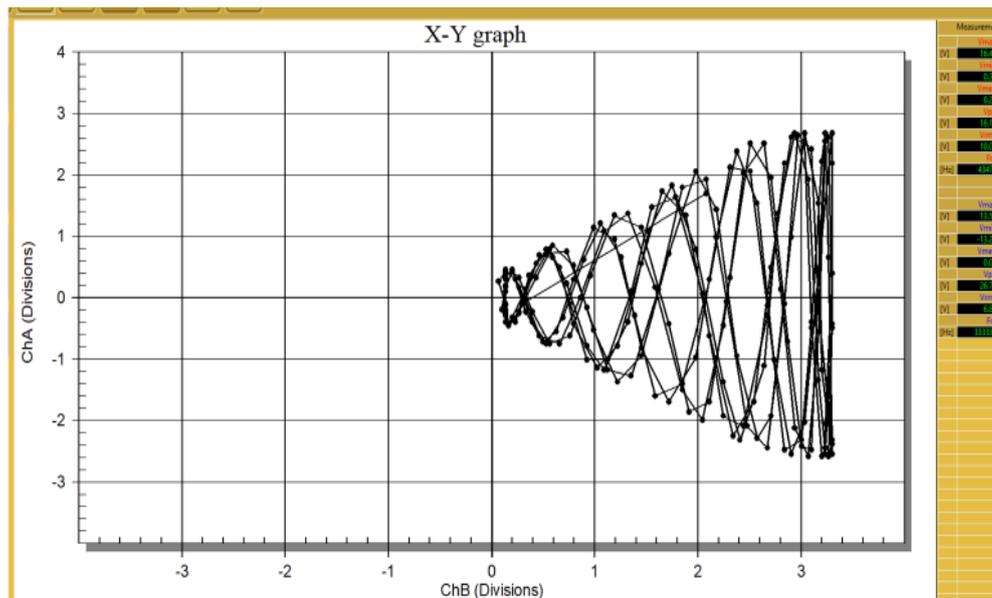
Fig.9. Acquisition software for measurement of AM signals waveforms

The "thickness" of the lines within the trapezoid represents the high-frequency carrier signal, while the outer boundaries (the red outline mentioned in previous responses) follow the shape of the lower-frequency modulating signal.
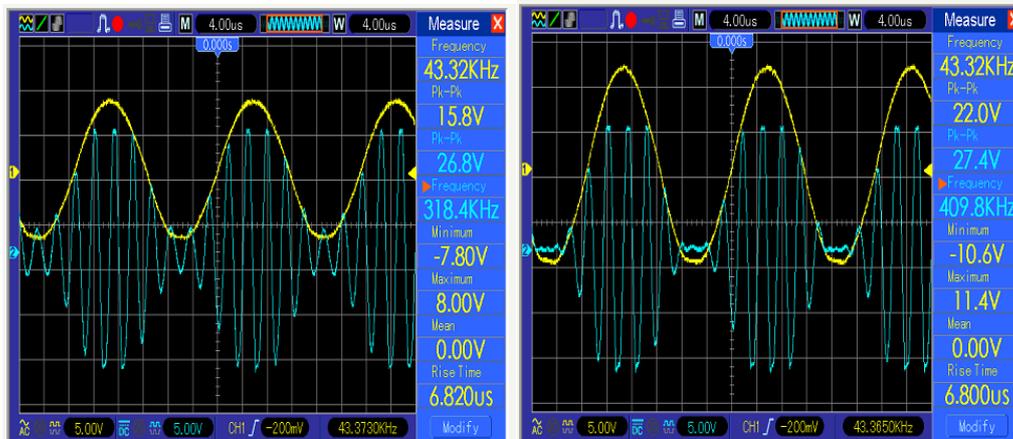

Fig.10. The shape of the lower-frequency modulating signal

5. CONCLUSIONS

This paper presented a comprehensive investigation of an amplitude modulation circuit based on mathematical modeling, MATLAB-based simulation, and laboratory experimentation. An analytical model of the AM process was developed and used as a theoretical reference to describe the relationship between the modulating signal, carrier signal, and resulting modulated waveform. The analytical expressions accurately predicted the spectral components and modulation behavior under ideal operating conditions.

MATLAB simulations were employed to validate the theoretical model and to examine the influence of key parameters such as modulation index, carrier frequency, and modulating frequency.

The simulation results demonstrated close agreement with analytical predictions and provided additional insight into system behavior through time-domain and frequency-domain analyses.

Experimental measurements conducted using an analog multiplier (AD633) confirmed the feasibility of the proposed implementation and highlighted the impact of non-ideal circuit effects, including gain variations and bandwidth limitations. Despite these practical constraints, the measured AM waveforms exhibited good consistency with both analytical and simulation results, validating the robustness of the proposed modeling and simulation framework.

The comparative analysis of analytical, simulation, and experimental results demonstrates that the combined methodology offers a reliable and effective approach for the analysis and validation of amplitude modulation circuits. This integrated framework reduces the gap between theoretical concepts and practical implementation, providing a

solid basis for both technical evaluation and instructional use in analog communication systems.

REFERENCES

[1]. Dobra R., Buica G., Pasculescu D., Leba M., *Safety management diagnostic method regarding work cost accidents from electrical power installations*, In Proc. 1st Int. Conf. on Industrial and Manufacturing Technologies (INMAT), Vouliagmeni, Athens, Greece, 2013.

[2]. Lathi B. P., Ding Z., *Modern Digital and Analog Communication Systems*, 4th ed.; Oxford University Press: New York, NY, USA, 2010.

[3]. Jooseung K., et al., *Analysis of envelope-tracking power amplifier using mathematical modeling*, IEEE Transactions on Microwave Theory and Techniques 62.6, pp.1352-1362, 2014

[4]. Journee H. L., *Demodulation of amplitude modulated noise: a mathematical evaluation of a demodulator for pathological tremor EMG's*, IEEE Transactions on Biomedical Engineering 5, pp. 304-308, 2007.

[5]. Hans R., *Amplitude, phase, and frequency modulation*, Proceedings of the Institute of Radio Engineers 19.12, pp. 2145-2176, 2006.

[6]. Farman M.A., Mortada D. H., *Simulation and Implementation of Amplitude-Shift Keying Modulation in Digital Communication Systems: A Practical Approach*, Bilad Alrafidain Journal for Engineering Science and Technology 3.1, pp.20-3, 2024.

[7]. Best R. E., *Phase-Locked Loops: Design, Simulation, and Applications*, 6th ed.; McGraw-Hill: New York, NY, USA, 2007.

[8]. Proakis J. G., Salehi M., *Fundamentals of Communication Systems*, 2nd ed.; Pearson Education: Boston, MA, USA, 2014.

[9]. * Analog Devices, AD633: Low-Cost Analog Multiplier*, Datasheet; Analog Devices Inc.: Norwood, MA, USA, 2021.

[10]. * MathWorks, MATLAB and Simulink User Documentation*, MathWorks Inc.: Natick, MA, USA, 2023.