Faculty of Engineering & Technology
Department of Electrical & Computer Engineering
ENEE4113-COMMUNICATIONS LAB

Exp 4: Frequency Modulation

Report #1

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1. Abstract

The main objective of this experiment is To bring practice into FM theory. It also tries to achieve specific objectives such that to be familiar with basic communication knowledge such as doing FM modulation and demodulation, having knowledge about the sensitivity of the FM modulator and acknowledging the carrier zero crossing. Likewise, it briefly explains several fundamental ideas regarding the signals like the low pass filter properties along with the meaning and relevance of pre-emphasis in this field. This constructive approach is meant to improve the working knowledge on FM basics so as make a comparison between what is taught in class and how it is in the real life situations.

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2. Theory

2.1 Frequency modulation

2.1.1 Definition of FM

Frequency Modulation is a modulation in which the frequency of the carrier wave is altered in accordance with the instantaneous amplitude of the modulating signal, keeping phase and amplitude constant. Modification of carrier wave frequency is performed for the purpose of sending data or information over small distances.[1]

The general expression of the FM modulated signal is as follows:

$s(t) = Ac \cos(2\pi fct + 2\pi kf \int_{-\infty}^{t} m(\alpha)d\alpha)$

where:

- Kf: Modulator sensitivity (Hz/V).
- Ac: Carrier Amplitude (V).
- fc: Carrier frequency (Hz).

2.1.2 Applications of FM

If we talk about the applications of frequency modulation, it is mostly used in radio broadcasting. It offers a great advantage in radio transmission as it has a larger signal-to-noise ratio, which means that it results in low radio frequency interference. This is the main reason that many radio stations use FM to broadcast music over the radio.

Additionally, some of its uses are also found in radar, telemetry, seismic prospecting, and in EEG, different radio systems, music synthesis as well as in video-transmission instruments. In radio transmission, frequency modulation has a good advantage over other modulation. It has a larger signal-to-noise ratio, meaning it will reject radio frequency interferences much better than an equal power amplitude modulation (AM) signal. Due to this major reason, most music is broadcasted over FM radio.[2]

2.1.3 Modulation Index (μ)

The modulation index is the ratio of maximum deviation in frequency of the modulating signal.

$$u = \frac{\Delta fmax}{fm} = \frac{kaAm}{fm}$$

2.1.4 Zero Carrier Crossings:

It's part of an FM modulated signal that occurs at the moments when in the spectrum of s(t) the carrier impulse is not observable meaning that there is no frequency deviation. These points are important for demodulation, because they point towards the changes between the different phases of the modulated signal in order to recover the signal and extract the information.

Zero carrier crossings can be determined using the spectrum of s(t) which can be written as: $s(f)= \frac{Ac}{2}\Sigma Jn(\beta)[\delta(f-fc-nfm) + \delta(f+fc+nfm)]$ so finding the values of β which makes $J0(\beta)=0$ which is a Bessel function term give the zero crossings.

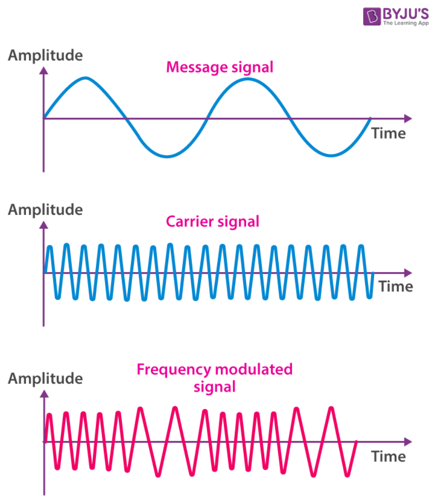

Figure1 :Waveform-for-frequency-modulation in time domain [2]

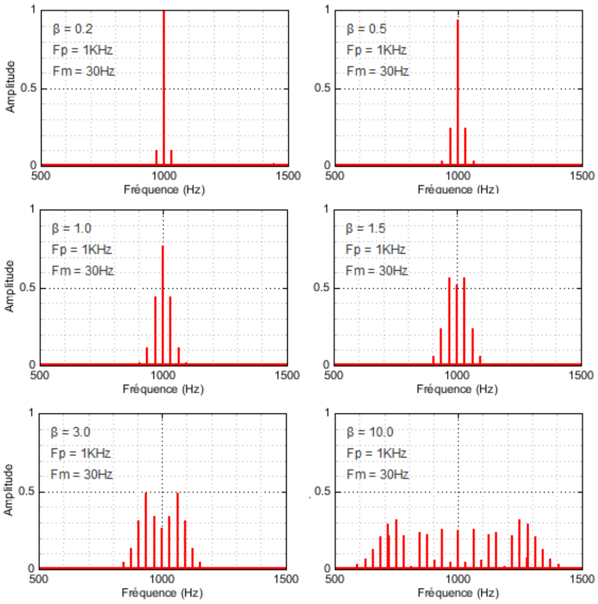

Figure 2:spectrum of fm signal [6]

From figure 1 it's clear that the frequency of a carrier increases when the amplitude of the input signal is increased. Here, the carrier frequency is maximum when the input signal is at its highest. Also, the frequency of a carrier decreases if the amplitude of the modulating signal goes down. What it means is that the carrier frequency is minimum when the input signal is at its lowest.

2.2 Frequency demodulated

2.2.1 Definition of Frequency demodulated

Frequency demodulation is the inverse of frequency modulation. The original modulating signal is obtained as output following demodulation. After the signal has been received, filtered, and amplified, the original modulation from the carrier must be recovered. This is known as demodulation or detection. [3]

2.2.2 Techniques for recovering the baseband signal from a frequency-modulated carrier

Frequency modulation offers improved performance over amplitude modulation, but it is somewhat more difficult to extract the original information from an FM waveform. There are a few different ways to demodulate FM :

- ❖ The High-Pass Filter:
  We converted frequency modulation to amplitude modulation by using the filter. This is a useful way of FM demodulation because it enables us to use envelope-detector circuitry designed for use with amplitude modulation. The filter used to generate this waveform was simply an RC high-pass with a cutoff frequency close to the carrier signal. [3]

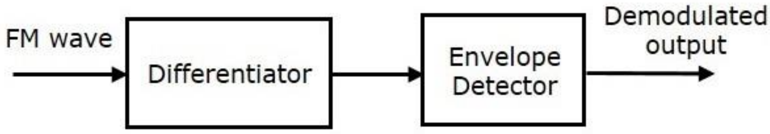

Figure 3: FM demodulator using frequency discrimination method [4]

- ❖ Using the Phase-Locked Loop Demodulator:
  A phase-locked loop (PLL) is used to build a complicated but high-performance FM demodulation loop. The intensity of an incoming waveform can be "locked onto" by a PLL. This is accomplished by combining a phase detector, a low-pass filter (also known as a "loop filter"), and a voltage-controlled oscillator (VCO) into a negative-feedback system.
  The phase detector generates a signal proportional to the phase difference between the incoming waveform and the VCO output. The loop filter smoothens this signal, which then serves as the VCO's control signal. As a result, if the intensity of the input signals is constantly increasing and decreasing, the VCO control signal must also increase and decrease for the VCO output frequency to remain equal to the input frequency. [3]

  There are three main components in a PLL:

  1. Phase detector : generates a voltage, which represents the phase difference between two signals. In a PLL, the two inputs of the phase detector are the reference input and the feedback from the VCO. The PD output voltage is used to control the VCO such that the phase difference between the two inputs is held constant, making it a negative feedback system . [7]

2. Voltage-Controlled Oscillator : contains an adjustable tuning element, such as a reactor diode with a capacitance that changes depending on the input voltage. The PLL circuit is thus a kind of feedback control system for the VCO. The required input or control voltage to the VCO is often higher than the supply voltage available to the PLL circuit. [8]

3. Active low pass filter (Loop filter): It is used to filter and shape the control voltage applied to the Voltage-Controlled Oscillator (VCO), resulting in a DC voltage at the output after eliminating the high frequency component present in the phase output.

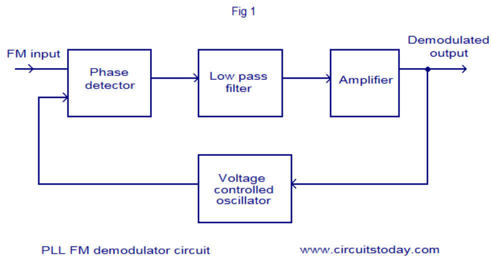

Figure 4:phase-locked loop (PLL) block [5]

2.2.2 Pre-emphasis and de-emphasis carrier

Pre-emphasis works by boosting the high-frequency portion of the signal. This compensates for the high-frequency loss in the cable.

De-emphasis works by cutting the low-frequency portion of the signal. This may be coupled with an increased transmit voltage.

Pre-emphasis and de-emphasis provide essentially the same function, which is to provide a flat frequency curve on the receiver side. In actual implementation, de-emphasis can be technically simpler, so it is more often seen between the two.

While pre/de-emphasis helps to create a more stable signal, it can also create issues if the system applies too much of either. For instance, if surpass the optimal amount, it can end up with too little low-frequency and too much high-frequency. [9]

3. Procedure and data analysis

3.1 Modulation:

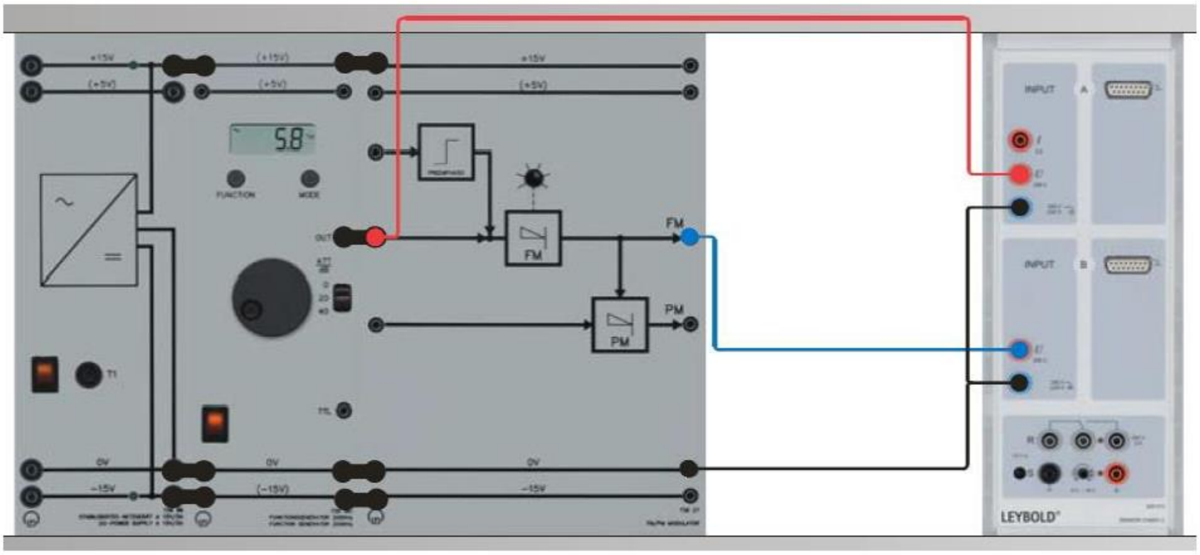

Figure 5:FM modulation circuit

3.1.1 Displaying the message signal in the time and frequency domain:

we Set the function generator to generate a sinusoidal message signal with Vss = 20V and fm = 1kHz. And set the carrier knob to the min value and start the measurement.

First we set the modulated signal to 0 to see the message signal in time and frequency domain

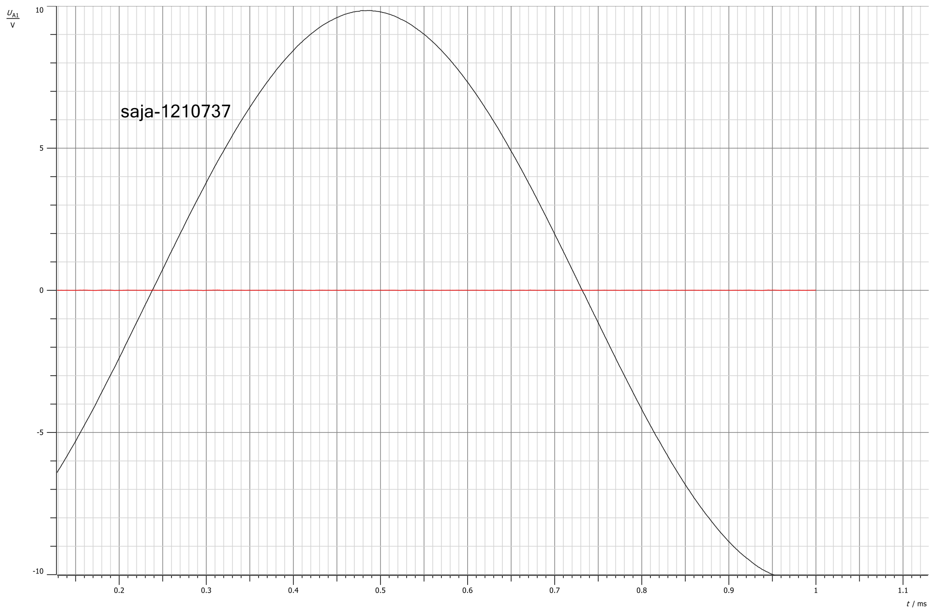

Figure 6: Display one message period in time domain with Vss=20V and fm=1kHz.

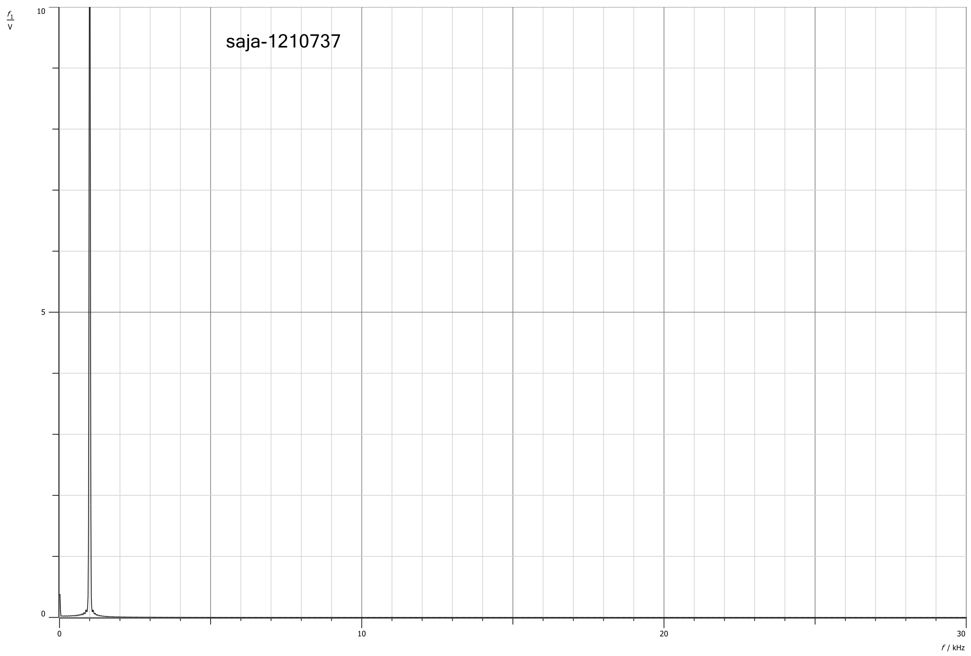

Figure 7:Message Signal in frequency domain with Vss=20V and fm=1kHz.

As it can be noticed from the overall representation of the FM modulated signal which is s(t) = Ac cos (2πfct + 2πkf $\int_{-\infty}^{t} m(\alpha)d\alpha$) , the frequency of the carrier signal is altered corresponding to the change in the message signal's amplitude (Am). Intermodulation implies that the carrier signal has more variations in terms of the frequencies than in its center frequencies. Really, in this experiment Δf = KfAm was small, so the difference in frequencies in the modulated signal did not reveal great differences. Therefore, the findings from this section opposed the theory results.

3.1.2 Setting the carrier frequency to exactly 20kHz

In this section we Set the function generator to give a Vss = 0V message signal. Now the modulated signal s(t) is representing the carrier signal alone , which is prove below:

s(t) = Ac cos (2πfct + 2πkf $\int_{-\infty}^{t} m(\alpha)d\alpha$)

s(t) = Ac cos (2πfct + 0)

s(t) = c(t)

then In the frequency domain observe the carrier impulse and adjust it (using the carrier knob) to be on the 20kHz frequency x-axis point.

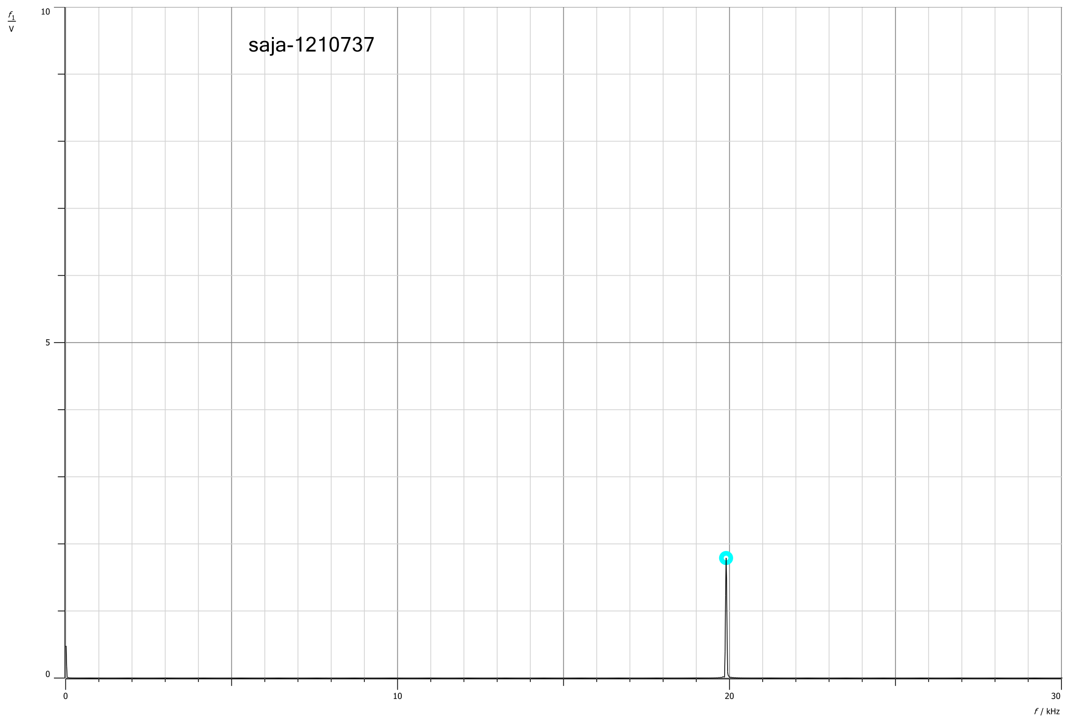

Figure 8:spectrum when Setting carrier frequency to 20kHz

As we know, the instantaneous frequency of the modulated signal at any time is described by: $fi(t)=fc+kfm(t)$.

So, when the message signal was set to be constant, the instantaneous frequency remained constant as well.

And equation becomes→ $f \quad (t)=fc+kfm$ resulting in a constant frequency deviation from the carrier frequency.

At the end, the modulator sensitivity was represented by the slope and can be found using $\frac{\text{fi}-\text{fc}}{\Delta \text{m}}$.

Table 1:The carrier frequencies at different message voltages.

Message Voltage	Carrier Frequency	Message Voltage	Carrier Frequency
-10	19.32	2	20.11
-8	19.44	4	20.23
-6	19.58	6	20.34
-4	19.7	8	20.48
-2	19.84	10	20.6
0	19.97		

At point (10 ,-10) kf= $\frac{(20.6-19.32)*1000}{10- -10}$ = 64 Hz/v.

So, the frequency deviation for a 10V message signal was determined by:

Δf = KfAm= 64 *10 = 640 Hz.

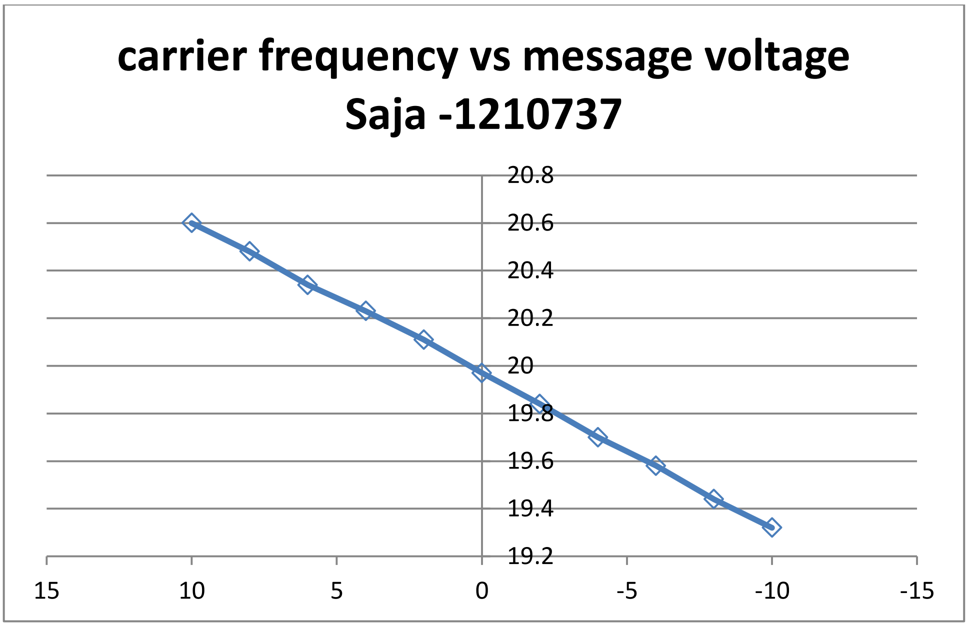

Figure 9: Carrier frequency vs. message voltage curve

3.1.3 Displaying the FM signal spectrum

First: Using sinusoidal signal with Vss=20v , DC offset is 0V and fm=3000Hz as the message signal m(t).

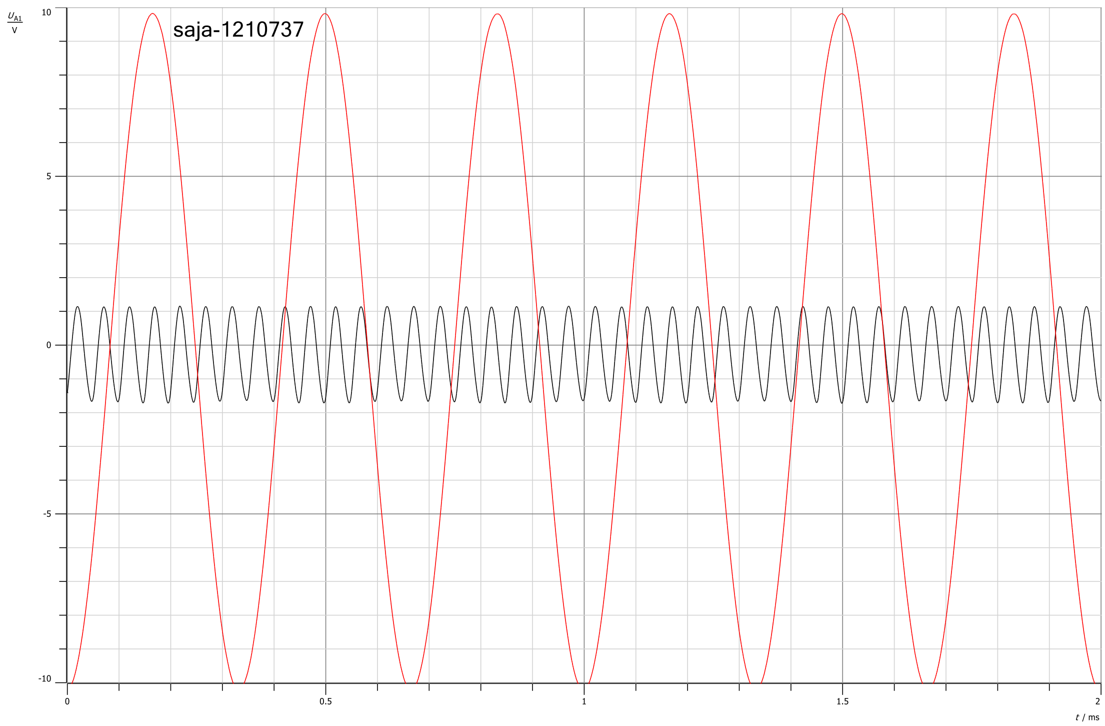

Figure 10:FM and message signals with vss=20V and fm=3000Hz in time domain

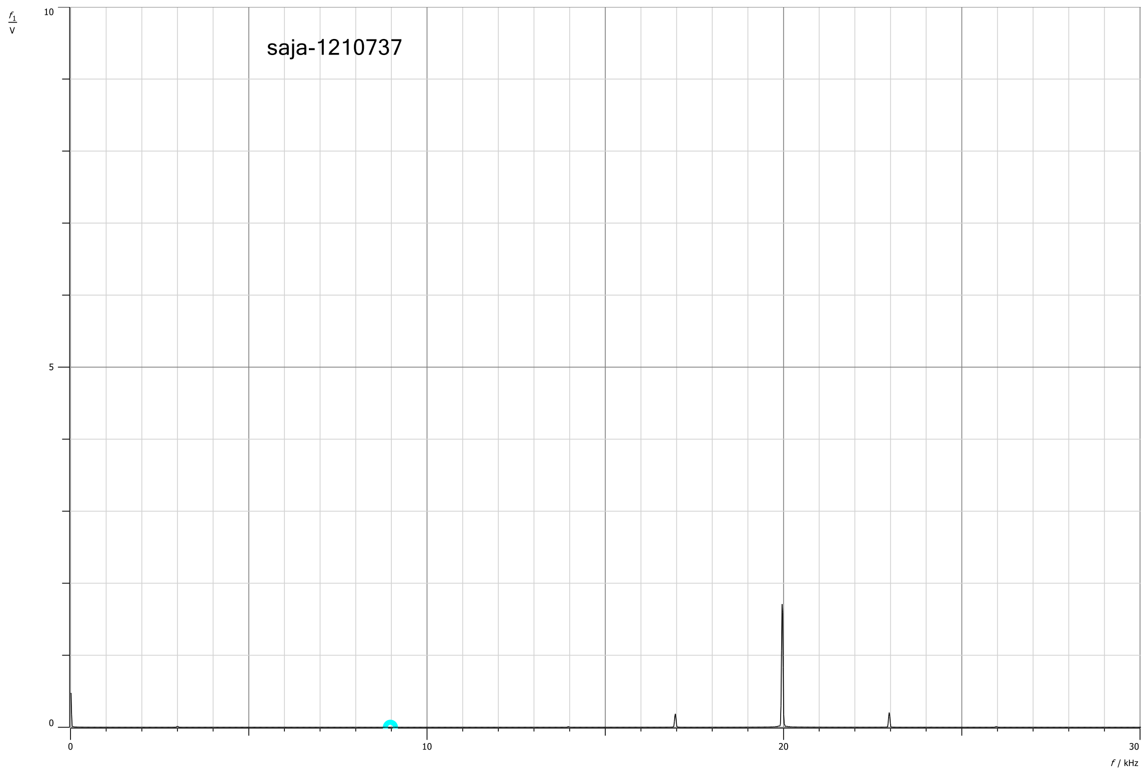

Figure 11:FM signal spectrum with vss=20V and fm=3000Hz

It was clear from figure 11 that there is 3 impulses at fc=20kHz, fc+fm = 23kHz and fc-fm = 17kHz and that the amplitude of the carrier changed linearly with the message amplitude.

In this case: $\beta = \frac{\text{KfAm}}{\text{fm}} = \frac{\Delta f}{\text{fm}} = \frac{64*10}{3000} = 0.213$ which is $\ll 1$ so the resultant FM modulated signal was narrowband and that's why it was similar to amplitude modulation.

Second: Using sinusoidal signal with Vss=20v and fm=200Hz as the message signal m(t):

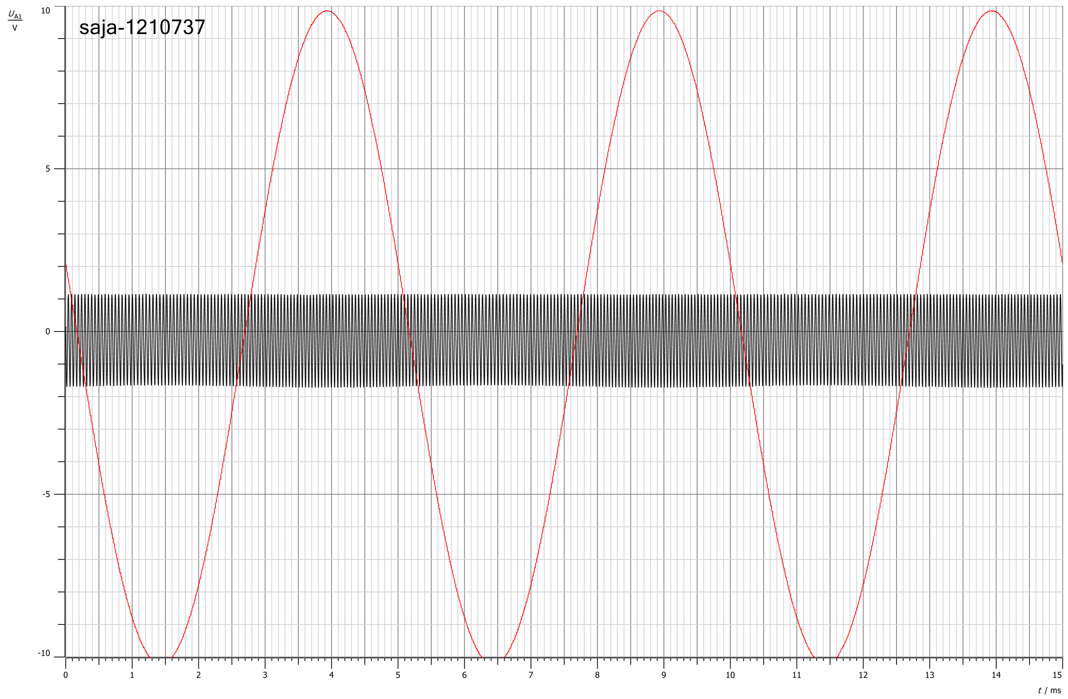

Figure 12: FM and message signals with vss=20V and fm=200Hz in time domain

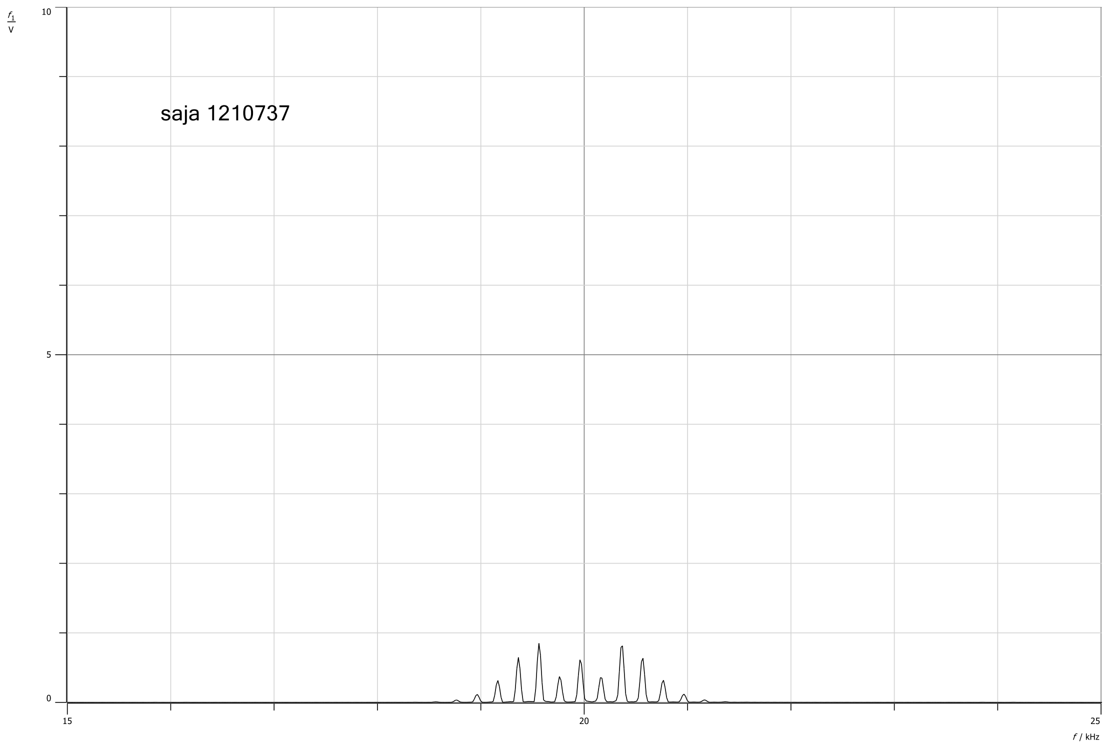

Figure 13:FM signal spectrum with vss=20V and fm=200Hz

From figure 13 it is clear that there are more than 3 impulses at fc+nfm ; n=0,1,1,…. 3

In this case: $\beta = \frac{\text{KfAm}}{\text{fm}} = \frac{\Delta f}{\text{fm}} = \frac{64*10}{200} = 3.2$ which is >1 so the resultant FM modulated signal was wideband and that's why we got a train of impulses.

From the comparison of two modulated signals it's clear that sidebands are more and bandwidth is larger in that signal which has higher frequency message. This is only possible if a higher frequency message signal results in wider spacing of the sidebands hence the overall width of the signal is large. For example, these signals where represented by the cosine functions raised to the base of the frequency without any modulations, one would notice a sequence of cosines multiplied with the Bessel functions of the modulation parameter (β). These Bessel functions show the variation of energy intensity through the spectrum; they clearly point at the existence and intensity of particular side bands in relation to the carrier frequency. According to these theories, the obtained results have reflected the outcomes of theoretical calculations, and it was found that no problems were observed.

3rd: message signal with square wave signal was used with Vss= 20V, duty cycle 50% and fm=200Hz to notice the changes in the spectrum for different m(t) types

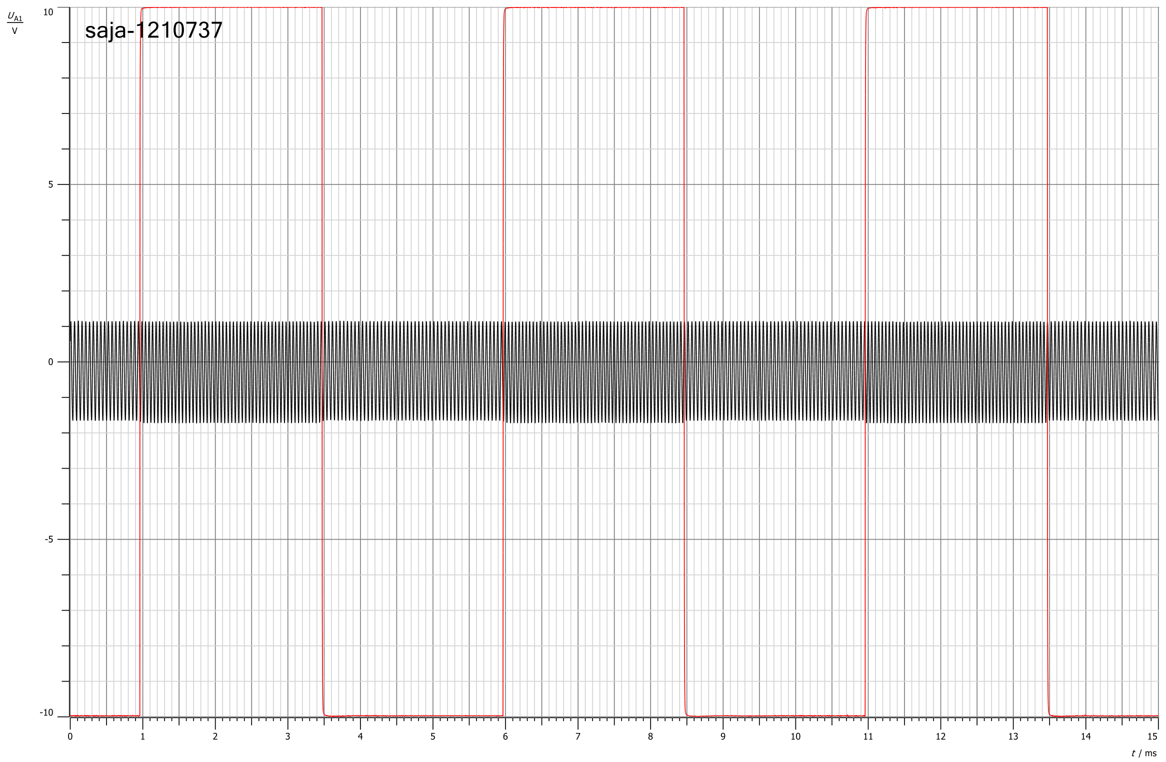

Figure14 :Square Message and modulated signals in time

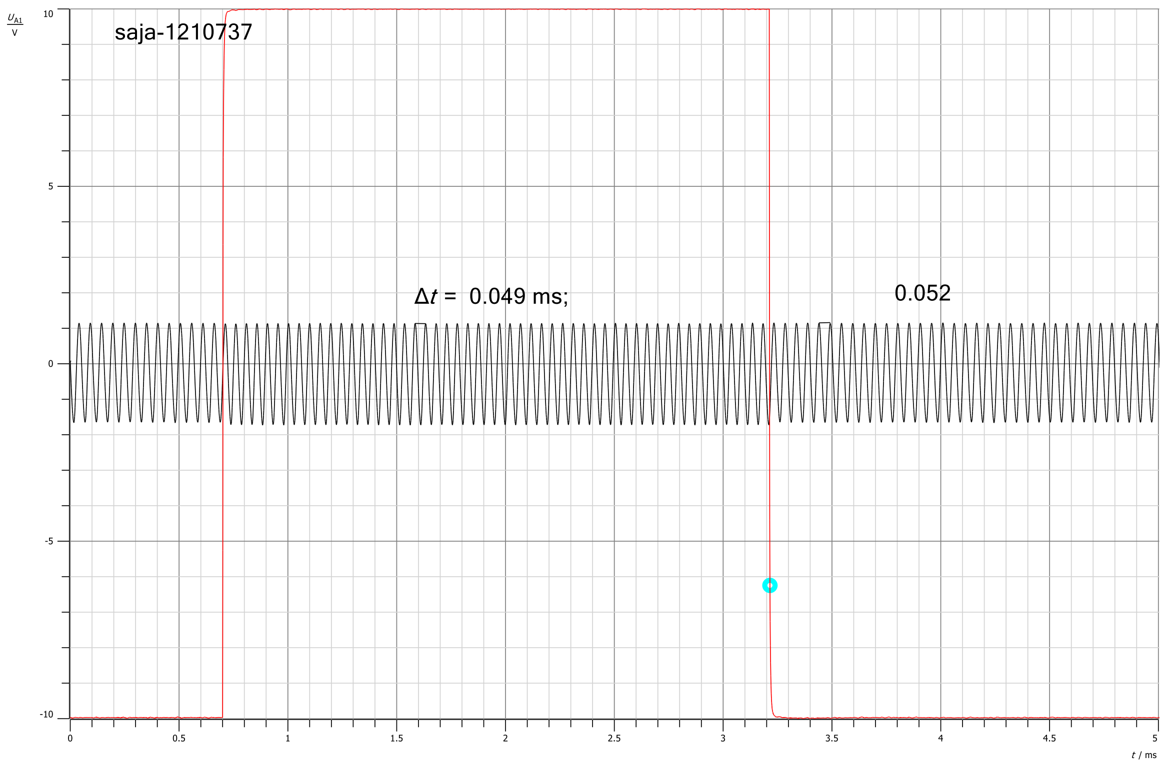

Figure 15:clear figure for square message and modulated signal in time

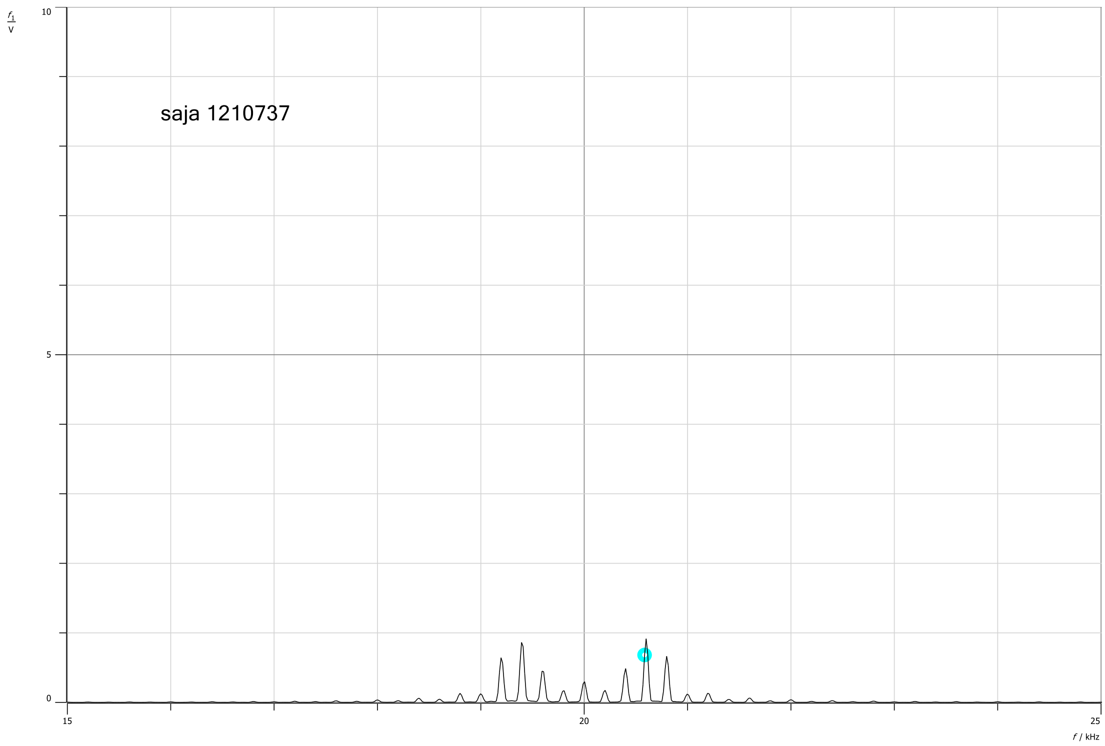

Figure 16:spectrum of modualted signal for square message

- With a sinusoidal message signal, the spectrum of the modulated signal displayed sidebands that were evenly spaced around the carrier frequency, with their amplitudes following a pattern described by Bessel functions. The bandwidth of the modulated signal was influenced by both the frequency deviation and the frequency of the sinusoidal message signal, encompassing the carrier frequency and additional components at multiples of the message signal frequency.

- In contrast, a square wave message signal, which contains odd harmonics, resulted in a more complex spectrum compared to a sinusoidal message signal. The spectrum included odd harmonics of the message signal frequency along with the sidebands of the carrier frequency. Consequently, the modulated signal had a wider bandwidth than that of a sinusoidal message signal due to the presence of higher-order harmonics.

- Overall, the primary differences lie in the complexity and bandwidth of the spectrum which is a sinusoidal message signal generates a simpler spectrum with evenly spaced sidebands, while a square wave message signal introduces additional odd harmonics which results in a more complex spectrum with a wider bandwidth.

3.1.4 Determining the zero carrier crossings

As the spectral component at a carrier frequency is proportional to the Bessel function term J0(β), there are certain values of β cause J0(β) to equal 0. The initial three values are: β = 2.4048, β = 5.5201, and β = 8.6537. To achieve zero crossing (varying β), we can either vary the message amplitude (while holding the frequency constant) or vary the frequency (while keeping the amplitude constant).

1st : A message with a constant frequency of 100Hz

We have a frequency and modulation index , so can calculate the amplitude using this equation → $\beta = \frac{kf\ Am}{fm}$ → Am=$\frac{\beta\ \mathrm{fm}}{kf}$

Table2 :Determining the zero carrier crossings using constant frequency

Modulation index (β)	**2.4048**	**5.5201**	**8.6537**
Amplitude (V)	3.7575v	8.6252v	13.5214v

When β= 2.9408 → Am=$\frac{2.4048*100}{64}$ =3.7575v

When β= 5.5201 → Am=$\frac{5.5201*100}{64}$ =8.6252v

When β= 8.6537 → Am=$\frac{8.6537*100}{64}$ =13.5214v

Here we use a sinusoidal signal with VSS = 0V and fm = 100Hz of the function generator as the modulating signal m(t). Slowly Increase the amplitude of the message to be 3.5757 which means Vss= 2* 3.7575 = 7.5151

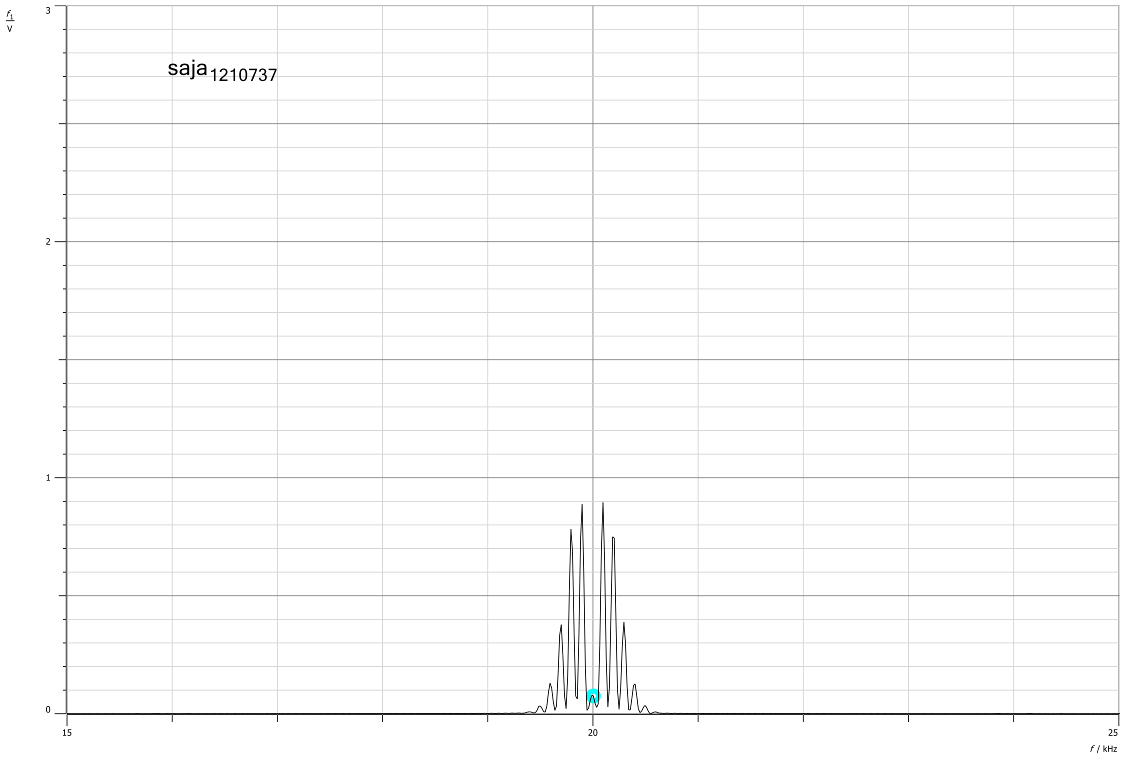

Figure17 :FM modulated signal with constant frequency (100Hz) and vss= 7.5v

The 1st carrier decay is at amplitude = 7.5/2=3.75v
It is clear that the carrier impulse disappeared at Am=3.7575v , it was equal 0.07 which is almost zero.
After comparing theoretical and practical results, it is clear that they are very close with a kind of error resulted from the fact that the components used in the experiment are not ideal or there were simple errors during the experiment.

2nd : Varying the message frequency while keeping the amplitude constant (10v).
We have the amplitude and modulation index , so can calculate the frequency using this equation
→ $\beta=\frac{kf\ Am}{fm}$ → $fm=\frac{kf\ Am}{\beta}$

Table3 : Determining the zero carrier crossings using constant amplitude

Modulation index (β)	**2.4048**	**5.5201**	**8.6537**
Frequency (Hz)	266.1322 Hz	115.9399Hz	73.9568 Hz

When β =2.4048 then $fm=\frac{64*10}{2.4048}$= 266.1322Hz
When β =5.5201 then $fm=\frac{64*10}{5.5201}$= 115.9399Hz
When β =8.6537 then $fm=\frac{64*10}{8.6537}$= 73.9568Hz
Here we use a sinusoidal signal with VSS = 20V and fm = 1kHz of the function generator as the modulating signal m(t). Slowly reduce the frequency of the message to be 266.1Hz .

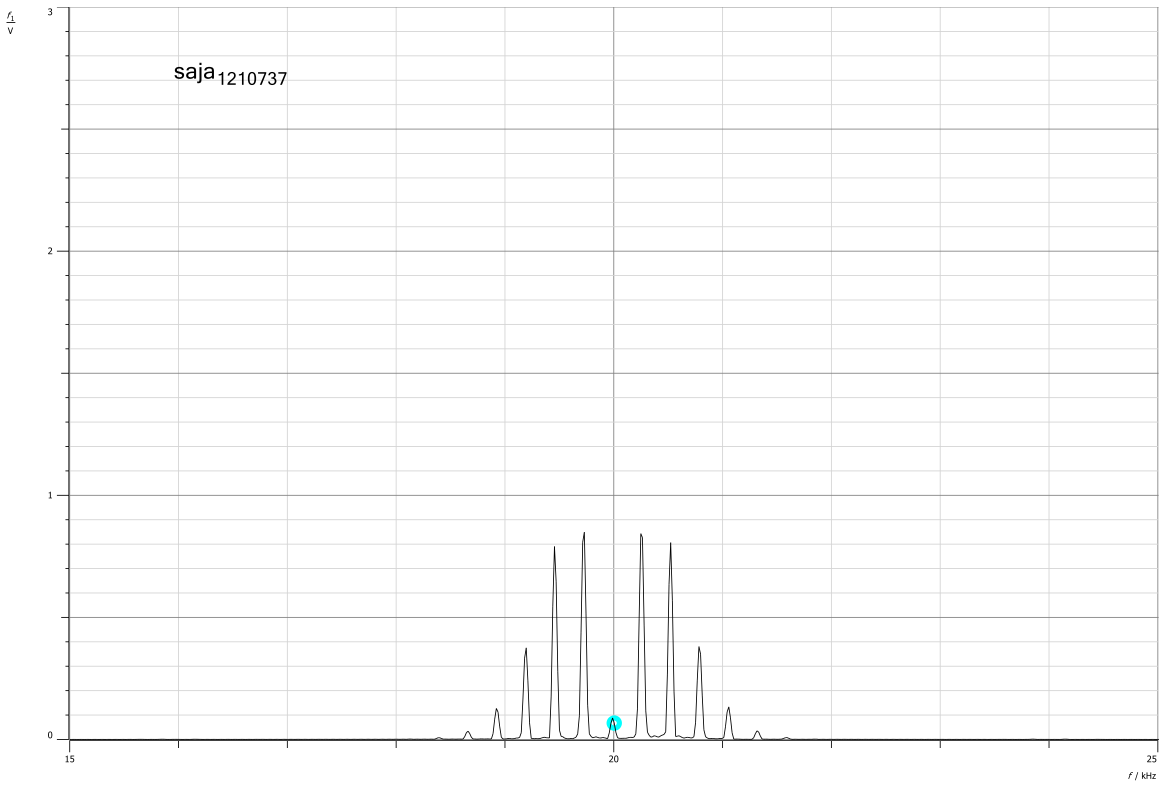

Figure18 :FM modulated signal with constant amplitude (10V) and fm = 266.1Hz

The 1st carrier decay is at frequency= 266.1 Hz
It is clear that the carrier impulse disappeared at fm =266.1Hz, it was equal 0.07 which is almost zero.
After comparing theoretical and practical results, it is clear that they are very close with a kind of error resulted from the fact that the components used in the experiment are not ideal or there were simple errors during the experiment.

3.2 Demodulation:

3.2.1 Time and frequency domain FM demodulated signal

In this section we Use a sinusoidal message signal m(t) with VSS = 10 V and fm = 500 Hz. Set the loop filter of the FM demodulator to τ2.

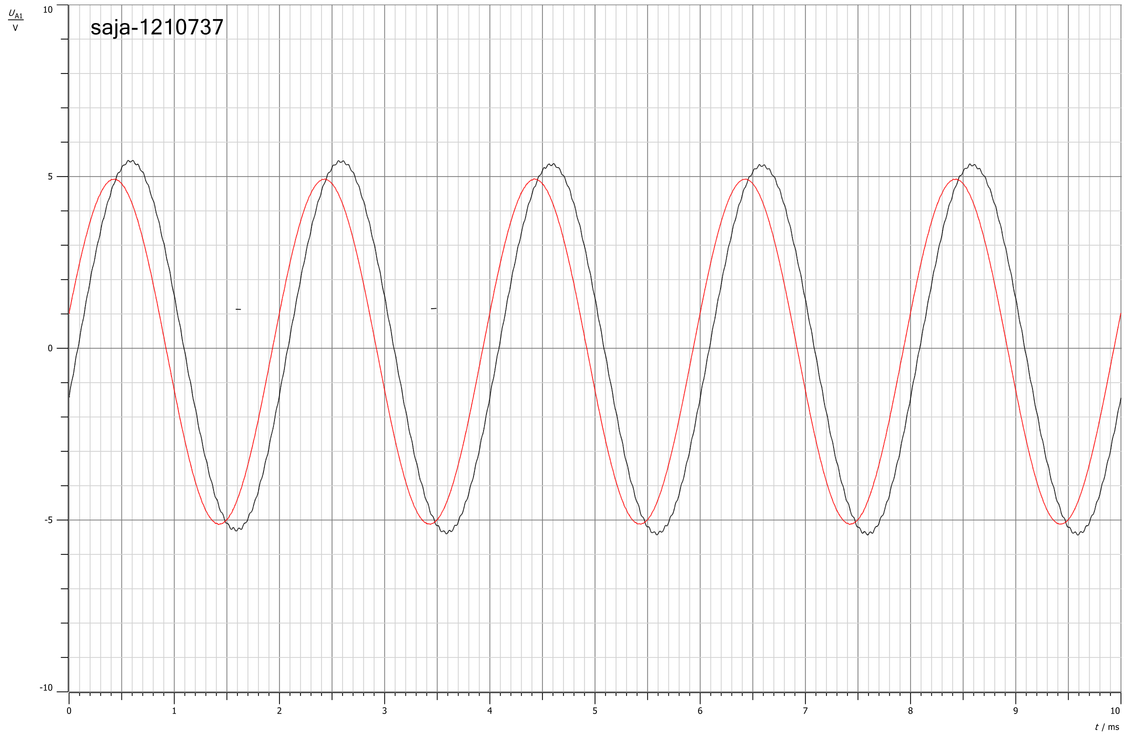

Figure19 : Message and demodulated signals in time domain

Figure 20: spectrum ofMessage and demodulated signals

It was clear that the PLL demodulator successfully extracted the baseband message signal from the FM signal, as the demodulated signal closely matched the original message signal in shape, exhibiting minimal distortion or noise. This minimal distortion or noise was due to the nature of the filter and the components used in the experiment. Thus, the PLL demodulator proved to be effective for FM demodulation.

3.2.2 Studying the effect of the receiver loop filter

In this section two receiver loop filters were used, with each representing a low pass filter with a unique gain characteristic. And the aim of this section is to compare the message signal with the demodulated signal when the gain of the loop filter is varied between the two loop filters.

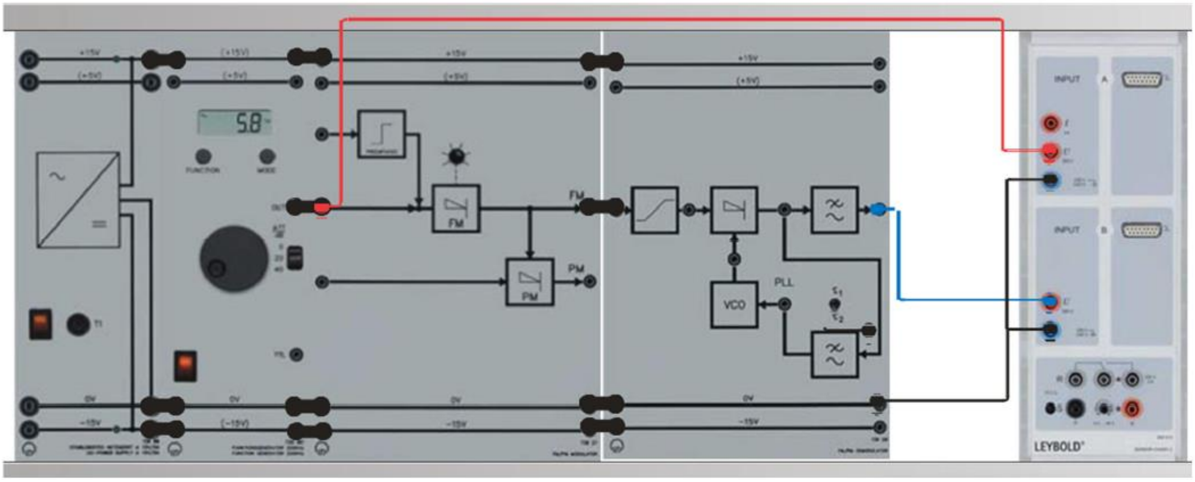

Figure 21: FM demodulation circuit

3.2.2.1 Studying Loop filters τ1 and τ2 without pre-emphasis

A sinusoidal modulating signal with Vss=4v and fm=500Hz was used in this part to plot Ad/Am versus fm after determining the amplitude of the demodulated signal (Ad) at multiple values of fm, using the spectrum for each loop filter.

Table 4: Studying Loop filters τ1 and τ2 without pre-emphasis.

Message frequency (HZ)	**500**	**1000**	**1500**	**2000**	**3000**
Ad using τ1 filter	8.84	4.30	2.86	2.09	1.18
Ad using τ2 filter	2.72	2.54	2.47	2.24	1.44

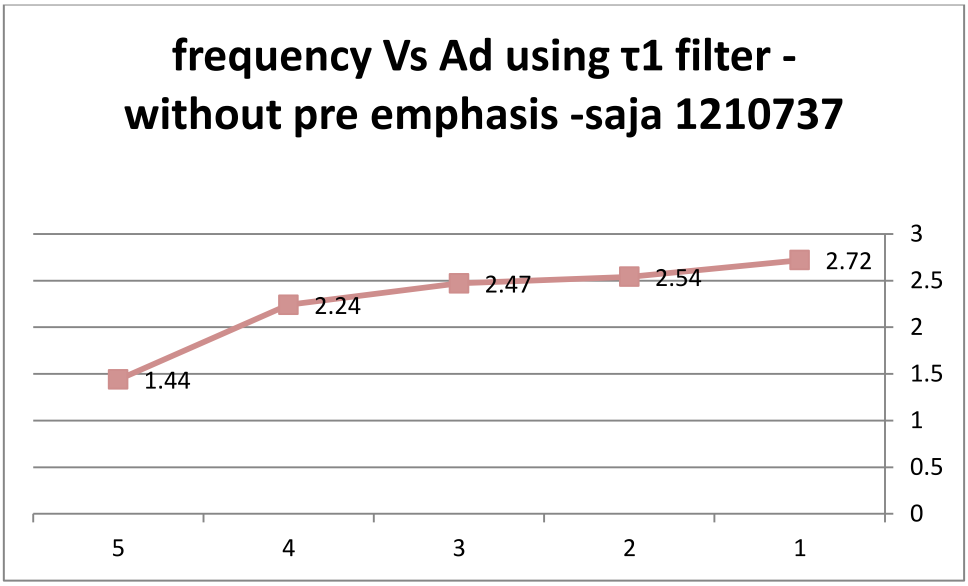

Figure 22:Loop filter τ1 chart without pre-emphasis

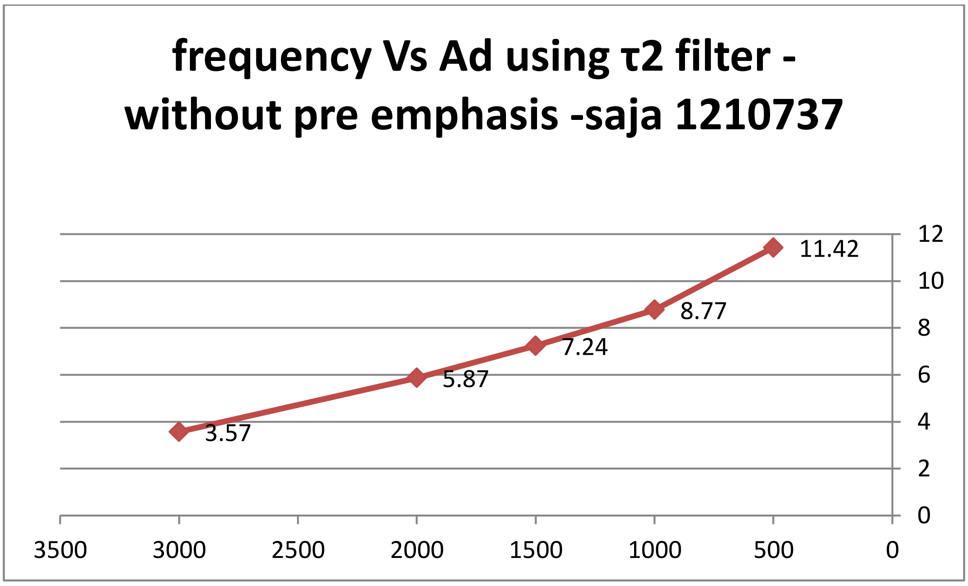

Figure 23: Loop filter τ2 chart without pre-emphasis

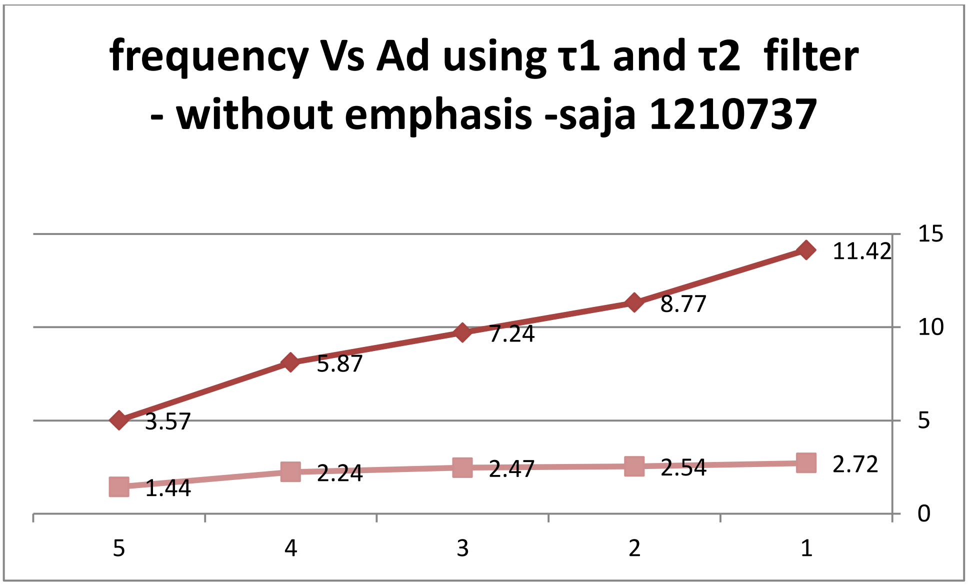

Figure 24:Loop filters τ2 and τ1 charts without pre-emphasis

- τ1 primarily focuses on filtering out high-frequency noise and interference from the demodulated signal while maintaining stability. It is noticeable that as the frequency increases, the gain (Ad/Am) decreases. Consequently, at higher frequency deviations, the gain might begin to deviate due to the filtering limitations of τ1.

- On the other hand, using loop filter τ2 results in a more stable and linear relationship between gain (Ad/Am) and frequency deviation (Fm) compared to τ1. τ2 provides additional filtering and signal conditioning, producing a cleaner and more refined demodulated signal. The gain difference between frequencies was relatively small, and as the frequency increased, the gain decreased. Therefore, τ2 enhanced the demodulator's performance, especially at higher frequency deviations where τ1 might show limitations.

3.2.2.2 Studying Loop filters τ1 and τ2 with pre-emphasis

Pre-emphasis is the process of amplifying its input signal if it is at a specific range of frequency (Usually high frequency).

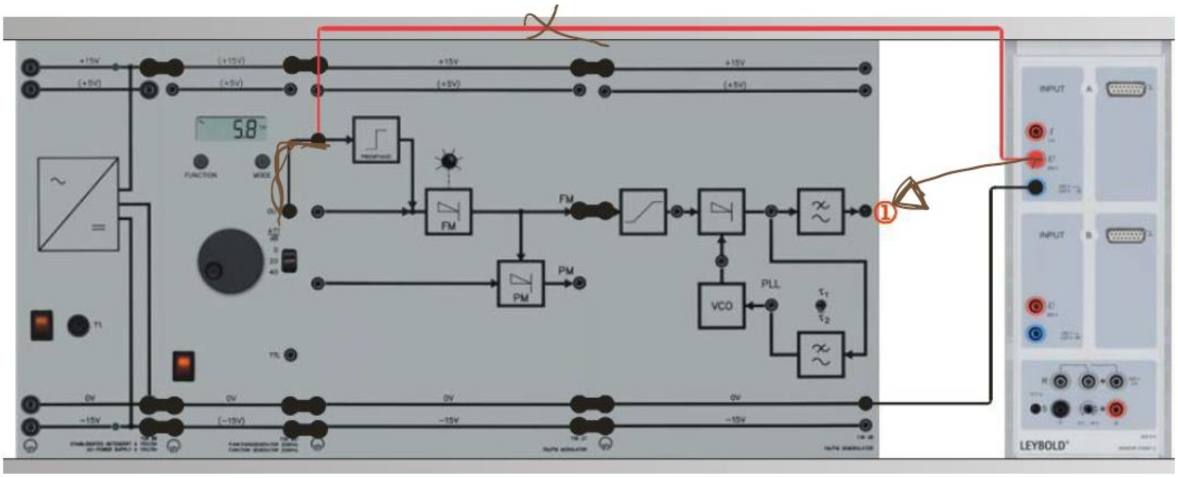

Figure25 : circuit for Pre-emphasis

We use a sinusoidal modulating signal m(t) with VSS = 4V and starting with fm = 500Hz. Determine the amplitude of the demodulated signal using the spectrum for each loop filter.

Table 5: Studying Loop filters τ1 and τ2 with pre-emphasis.

Message frequency (HZ)	**500**	**1000**	**1500**	**2000**	**3000**
Ad using τ1 filter	11.42	8.77	7.24	5.87	3.75
Ad using τ2 filter	3.5	5.19	6.27	6.3	4.26

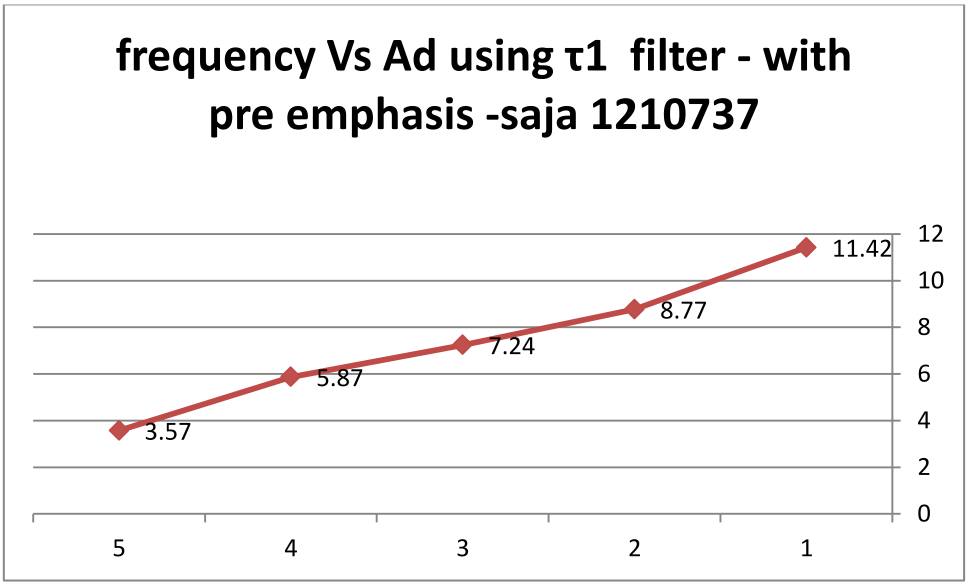

Figure 26: Loop filter τ1 chart with pre-emphasis

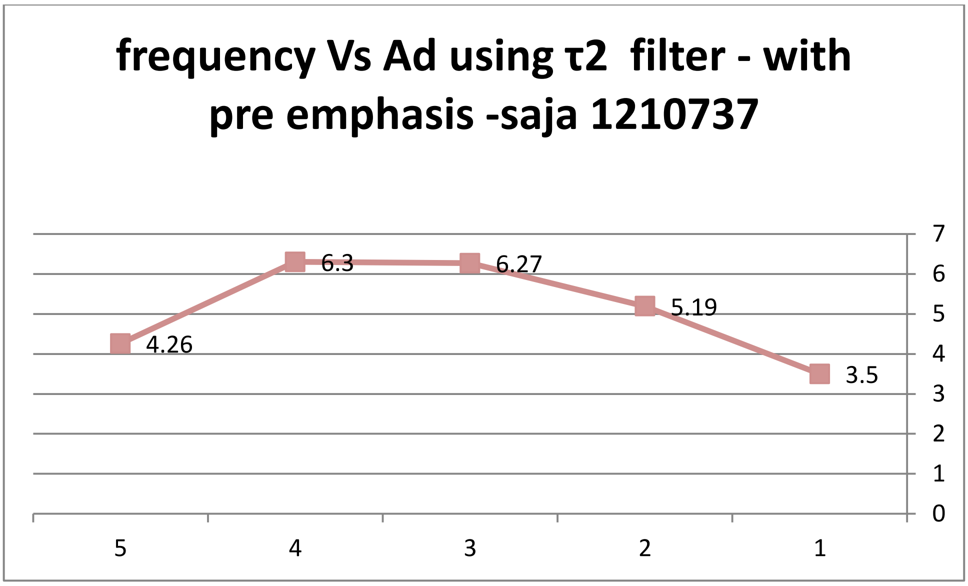

Figure 27: Loop filter τ2 chart with pre-emphasis

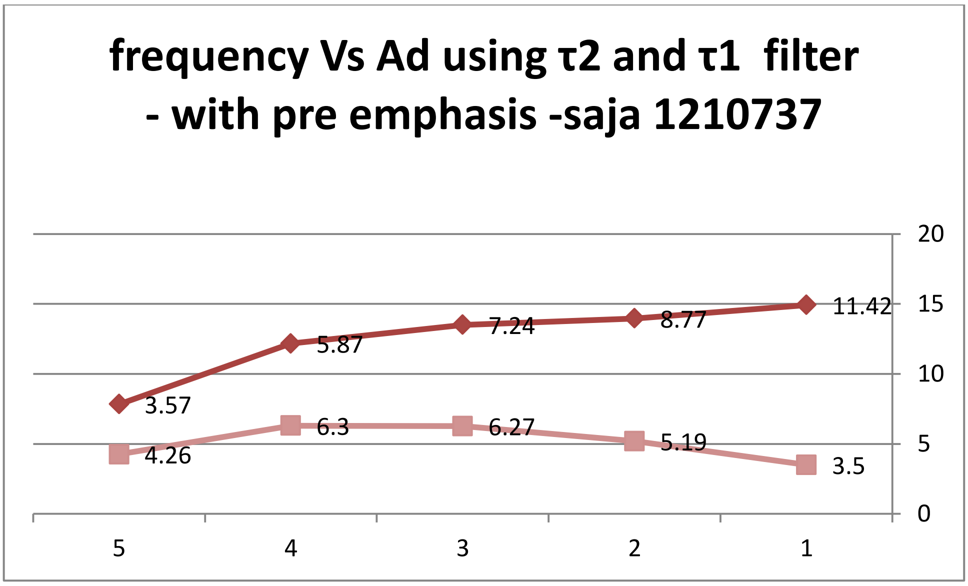

Figure 28:Loop filters τ2 andτ1 charts with pre-emphasis

When loop filters were used without pre-emphasis, noise had a more significant impact on higher frequencies. This effect was mitigated by using pre-emphasis, which increased the amplitude, deviation (Δf), and consequently the modulation index (β). As a result, noise immunity improved at higher modulating frequencies.

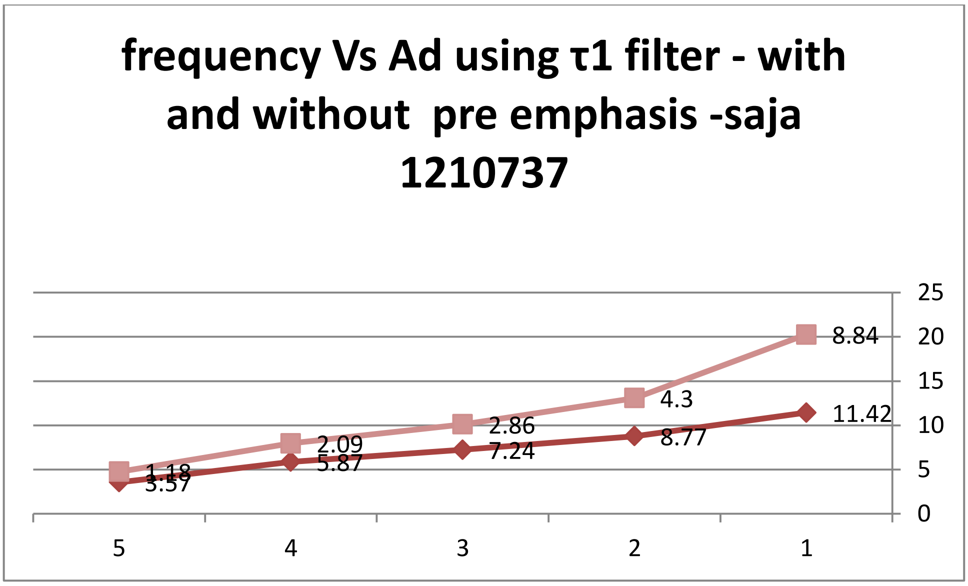

Figure 29: τ1 with and without pre-emphasis

As shown in Figure 29, the amplification of the τ1 filter decreased as frequency increased. Plotting loop filter τ1 with and without pre-emphasis revealed significant differences in demodulation performance. Without pre-emphasis, τ1 had a relatively stable gain (Ad/Am) versus frequency deviation (FM) relationship, but it was ineffective in handling high-frequency signals. In contrast, with pre-emphasis, τ1 improved the handling of high-frequency components, potentially leading to an increased signal-to-noise ratio (SNR) and reduced distortion in the demodulated output. However, τ1 with pre-emphasis may not be as effective as advanced filtering techniques like τ2, as shown in Figure 30.

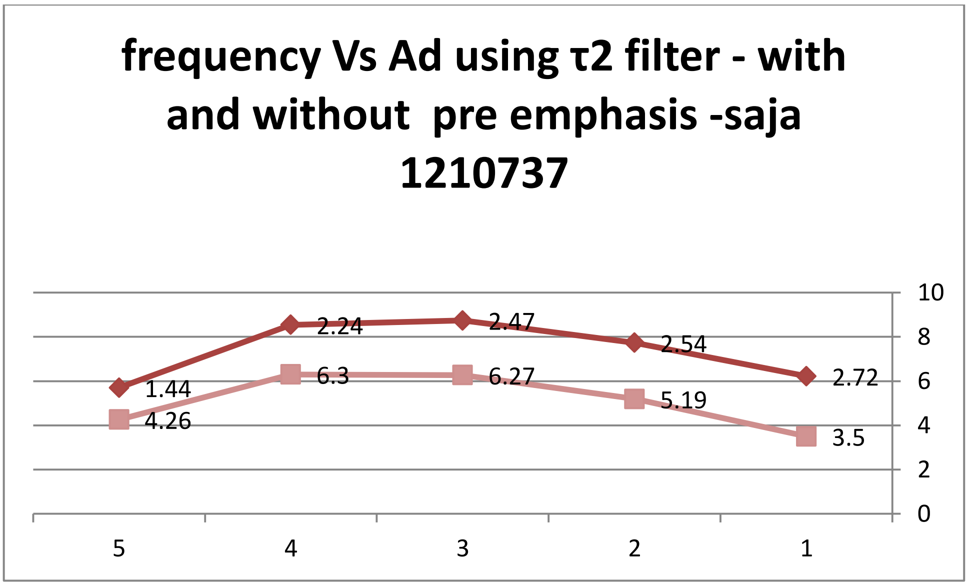

Figure 30: τ2 with and without pre-emphasis

Without pre-emphasis, the $\tau 2$ filter produces weaker signals as frequencies change. With pre-emphasis, signals are stronger across all frequencies using the same $\tau 2$ filter. Pre-emphasis significantly improves demodulation performance. Even without pre-emphasis, $\tau 2$ already exhibits better filtering and signal conditioning than $\tau 1$, resulting in higher stability, linearity, and signal-to-noise ratio (SNR) in the demodulated output. With pre-emphasis, $\tau 2$ further enhances these advantages by effectively handling pre-emphasized signals and achieving even greater stability, linearity, and SNR. Additionally, when using pre-emphasis, the gain increases until the frequency reaches 2000 Hz, after which it decreases up to the cutoff frequency.

4. Conclusion

In conclusion , FM modulation and demodulation are essential techniques in modern communication systems, making it important to study them in order to understand fundamental concepts such as the carrier zero crossing and FM modulator sensitivity, as well as signal basics like the characteristics of low pass filters and the applications of pre-emphasis. By the end of this experiment, my knowledge of FM modulation and demodulation has significantly improved, and I have gained insight into the various issues, methods, and concepts addressed during the experiment.

As can be seen, the experimental results closely matched the expected outcomes, and the connections were validated by tracing and comparing the resultant values or graphs with those obtained manually. The theoretical and practical results were nearly identical, and any discrepancies were minimal, likely due to the non-ideal nature of the components used or minor unnoticed errors in the connections.

5. References

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