The University of Calgary

Department of Electrical & Computer Engineering

ENEL 471-Introduction to Communication Systems and Networks

(Winter 2020)

Lab 4 : FM Modulation and Demodulation

Section date	B04: Tue. Mar. 24, 2020 B03: Tue. Mar. 31, 2020	B02: Wed. Mar.25, 2020 B01: Wed. Apr. 01, 2020
Location	Online	Online

This document consists of 2 parts:

Part I: Lab 4 Manual

- The lab consists of Simulink experiments and hardware experiments
- You MUST try to complete as much as you can of the Simulink experiments and answer the corresponding questions prior to Lab #4 session.
- You should download the Simulink files from D2L and run them locally.
- The hardware part involves transmitter & receiver, which takes longer to complete.
- You MUST read Lab #4 Manual prior to the Lab #4 session, otherwise you will have difficulty completing the hardware experiments by 5:00 pm.
- Students MUST leave the lab NO LATER than 5:00 pm.

Part II: Lab 4 Questions

- Answers to these questions must be submitted to the TAs at the end of the Lab period.
- Each group submits one set of Lab questions. Ensure names and ID numbers of the group members are written on the Lab answer sheets.

Acknowledgements

The ENEL 471- Introduction to Communications and Networks Lab 4 document was originally prepared by Jennifer A. Hartwell and Dr. Mike Potter, revised (January 2013) by Warren Flaman and Dr. Abu Sesay, revised (January 2015) by Mohamed Al Masri and Dr. Mohamed Helaoui, and revised (January 2018) by Leanne Dawson and Dr. Mohamed Helaoui.

Part 1

Lab 4 Manual

Introduction

There are two parts to this lab, the first part is simulation with Simulink and the second part is hardware based. The hardware section implements FM direct modulation using a VCO and demodulation using a PLL. To help you understand the hardware part, it is strongly suggested that the simulation part be done before the lab.

Important Formulas

- $\sin\varphi\sin\theta = \dfrac{\cos(\varphi - \theta) - \cos(\varphi + \theta)}{2}$
- $\cos\varphi\cos\theta = \dfrac{\cos(\varphi - \theta) + \cos(\varphi + \theta)}{2}$
- $\sin\varphi\cos\theta = \dfrac{\sin(\varphi + \theta) + \sin(\varphi - \theta)}{2}$

Background

In Lab #3, the concept of FM modulation was introduced. The formula used to implement FM is given by (1).

$$x_{\mathrm{FM}} = A_{\mathrm{c}}\cos[2\pi \mathrm{f_c t} + 2\pi \mathrm{k_f} \int_0^{\mathrm{t}} \mathrm{m}(\tau)\,\mathrm{d}\tau] \tag{1}$$

The reason for the integral is because phase and frequency are related by $\Delta f(t) = \dfrac{1}{2\pi}\dfrac{\mathrm{d}\phi(t)}{\mathrm{d}t}$, so an FM modulated wave is a carrier wave with frequency f_{c} that constantly varies in proportion with the message magnitude. How much it varies from the carrier defines the bandwidth of the modulated signal. This can be expressed by Carson's Rule given by (2).

$$BW \approx 2\,(\beta_{\mathrm{f}} + 1)\,B = 2\,(\Delta f_{\max} + B) \tag{2}$$

where $\Delta f_{\max}$ is the peak frequency deviation and β_{f} is the modulation index defined as $\beta_{\mathrm{f}} = \dfrac{\Delta f_{\max}}{B} = \dfrac{k_{\mathrm{f}}|m(t)|_{\max}}{B}$ and B is the bandwidth of $m(t)$.

It is intuitive that signal bandwidth, BW, is directly proportional to β_{f}, which is in turn directly proportional to k_{f} where k_{f} is just a weighting given to the message. The message is then inserted into the carrier as a frequency deviation and the more the frequency deviates, the more bandwidth it takes up.

1 Simulating FM Using Simulink

1.1 Direct FM Generation and PLL Demodulation

1.1.1 FM Spectrum

As was the case with AM, the easiest type of message to deal with analytically is a sinusoid. So to analyze the FM spectrum, we will consider tone modulation (when the message is a tone, B is denoted by f_{m} since the bandwidth of a tone is equal to the tone frequency).

Carson's rule solves for bandwidth only, but does not specify the exact shape of FM spectrum. If the message is $m(t) = \cos(2\pi f_{\mathrm{m}} t)$, then substituting $m(t)$ into (1) yields (3).

$$x_{\mathrm{FM}} = A_{\mathrm{c}}\cos[2\pi \mathrm{f_c t} + \beta_{\mathrm{f}}\sin(2\pi \mathrm{f_m t})] \tag{3}$$

Trying to take the Fourier series of something like this will prove very painful. So painful in fact, that when it comes to dealing with sinusoids of sinusoids, a whole new type of function was defined by our mathematical forefathers. This function was hence forth declared a 'Bessel Function', and it was provided for the people in many different 'kinds' and 'orders'. Students rejoiced over the Bessel Function because it came in a table.

The Bessel function that solves our current problem is the *Bessel function of the first kind and order n and is denoted as* $J_{\mathrm{n}}(\beta_{\mathrm{f}})$. Using the Bessel function to expand x_{FM} and then taking the transform, the magnitude spectrum of FM tone modulation is shown in (4).

$$|X_{\mathrm{FM}}| = \frac{A_{\mathrm{c}}}{2}\sum_{n=-\infty}^{\infty} |J_{\mathrm{n}}(\beta_{\mathrm{f}})|\delta(f - (f_{\mathrm{c}} + nf_{\mathrm{m}})) \tag{4}$$

The spectrum for FM tone modulation is just a sequence of deltas, centred around f_{c} (when n=0) with different weightings , $|J_{\mathrm{n}}(\beta_{\mathrm{f}})|$, that can be looked up in the Bessel function table. Note that $|J_{\mathrm{n}}(\beta_{\mathrm{f}})| = |J_{-\mathrm{n}}(\beta_{\mathrm{f}})|$ so our spectrum is symmetrical around f_{c}.

⇒ **Open the Simulink file 'fm_demodl.slx'**.

The file shows direct modulation of an FM signal using a VCO (Lab #3 stuff) and then it is fed to a PLL for demodulation. Do not worry about the demod portion yet. Only consider up to the point where it is marked 'FM Signal Here'.

Double-clicking on the VCO used for direct modulation shows what the current value of k_{f} ('input sensitivity') is. Double-clicking on the message generator (sinusoid message) reveals what the current frequency of the message is.

- Determine what the current value of β_{f} is. **(Ql)**

- Run the simulation. The figure that pops* up will show the FM signal's time and frequency domains. Please note that while the time domain sketch shows amplitude changes, that is just a consequence of discrete sampling done by the simulation. In theory, FM signals have constant amplitude. Sketch the spectrum and using the Bessel table mark down what the magnitudes and locations of the delta functions should be. **(Q2)**

***You need to close the figures in-between every simulation run.**
⇒ **Leave your Simulink file 'fm_demodl.slx' open.**

1.1.2 Demodulation with a PLL

In addition to direct FM modulation, lab #3 also introduced Phase Lock Loops. It was shown how PLLs could be used to track a carrier, which could in-turn be used to demodulate AM signals. Now you will see how PLLs can also be used to demodulate FM signals. Recall (or at least pretend to remember) that to track an incoming carrier a feedback loop was used that isolated the error between the VCO output's phase and the incoming signal's phase and then fed this error into the VCO to adjust it. Once the phases were locked at a 90° difference, the error voltage was zero, and so the loop was 'locked-on' and stopped adjusting.

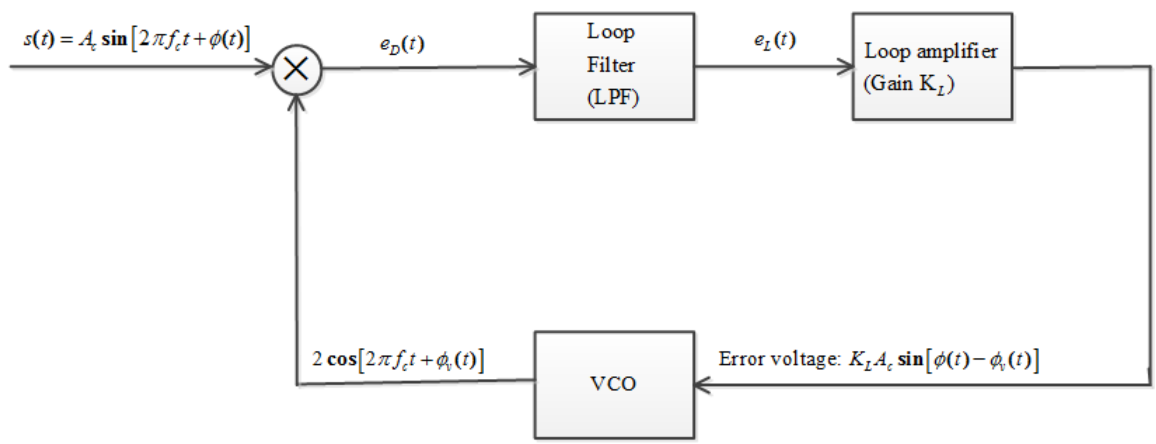


Figure 1: Block diagram of a basic PLL.

When instead of a phase error, we introduced a slight frequency error, the VCO output was still forced to a 90° phase difference from the incoming signal, but the error voltage did not because the feedback loop was constantly adjusting the VCO to track the frequency difference. Instead of going to zero, the error voltage centered around a value that was directly related to the frequency difference between the two signals.

Now what if the incoming signal to a PLL was an FM signal? The error voltage, which would track the frequency difference between the incoming signal and the VCO output signal, would actually be tracking the message signal. This argument has been based purely on what we saw from Lab #3 and intuition, if you require mathematical proof you are invited to read the lecture notes. For the lab, just working knowledge is sufficient.

- In **'fm_demodl.slx'** change the sinusoid message frequency to 4 Hz. Run the Simulation. Notice that the spectrum reacted accordingly by having the delta's squish closer together, and since β_f got larger, there are also more deltas with detectable power.
- Look at the time-domain 'error voltage' scope. What do you see? Is it what you expected? What is the approximate response time (the time it takes to reach steady state)? **(Q3)**
- Use the manual switch to change the input message so we are modulating the pulse train. Run the Simulation. Look at the error voltage again.
- What do you notice about the error voltage's response to the input when it steps up? Record the approximate response time. **(Q4)**
- In lab #3, you saw how changing the loop's gain factor affected response time. Prove this again by changing the gain to 2 and re-recording the response time for the pulse train. Which gain produces a faster response? **(Q5)**

⇒ **Close file 'fm_demodl.slx'**.

1.2 FM Immunity to Non-Linearity and Indirect Modulation

1.2.1 Immunity to Non-Linear Devices

⇒ **Open the Simulink file 'immunity.slx'**.

You should notice that there are two types of tone modulation on the left side - AM and FM. One at a time, the modulated signals can be fed into a 'non-linear device'. In our case the non-linear process is defined by the output-input equation (5), where $u(t)$ is the input and $y(t)$ is the output.

$$y(t) = u(t) + 2u^3(t) \tag{5}$$

Non-linear devices are very common in practice (remember the diode in lab #2). Non-linear devices result in harmonics, or higher frequency components that are multiples of the input frequency.

In our Simulink model, we follow the non-linear device with an LPF centred at the carrier frequency, which removes the harmonics. In practice this should be a BPF, however, the carrier frequency is so low that we can use an LPF. We are treating the non-linear process as an unwanted phenomenon and try to recover just the original modulated signal back.

- Run the simulation for both inputs and comment on how (for each case) the spectrum was changed by the process. Don't forget to close the figures between runs. Using the general formulas for AM and FM signals and the non-linear process equation used in the simulation, show why the 'after' spectra look the way they do. (Doesn't have to be precise math, just refer to the message as m(t)) **(Q6)**

⇒ **Close 'immunity.slx'**.

1.2.2 Indirect FM Modulation

Creating an FM signal using a VCO is called direct modulation because the VCO invokes the equation for an FM signal exactly. Also, think back one more time to lab #3, it was shown that a narrowband FM signal spectrum is identical to that of an AM signal. To see why this is so, consider our message to be a cosine, plug it into the FM equation given by (6), and then apply a trig-identity. Thus, our FM signal is :

$$\begin{aligned} x_{\mathrm{FM}} &= A_{\mathrm{c}}\cos[2\pi f_{\mathrm{c}}t + \beta_{\mathrm{f}}\sin(2\pi f_{\mathrm{m}}t)] \\ &= A_{\mathrm{c}}\cos[\beta_{\mathrm{f}}\sin(2\pi f_{\mathrm{m}}t)]\cos(2\pi f_{\mathrm{c}}t) - A_{\mathrm{c}}\sin[\beta_{\mathrm{f}}\sin(2\pi f_{\mathrm{m}}t)]\sin(2\pi f_{\mathrm{c}}t) \end{aligned} \tag{6}$$

For narrowband FM, $\beta_f \ll 1$. Thus, equation (6) can be simplified to:

$$x_{\mathrm{FM}} = A_{\mathrm{c}}\cos(2\pi f_{\mathrm{c}}t) - \beta_{\mathrm{f}}A_{\mathrm{c}}\sin(2\pi f_{\mathrm{m}}t)\sin(2\pi f_{\mathrm{c}}t) \tag{7}$$

The equation shown in (7) can be implemented using multipliers and sinusoidal generators to implement narrowband FM. The two methods described above generate narrowband FM signals.

Suppose we want to generate a wideband FM (i.e., $\beta_f \gg 1$) signal. A narrowband signal could simply be put through some sort of frequency multiplier to generate a wideband FM signal. Consider this term again. If you did Part A (immunity) right, then you saw that the non-linear device created terms of the type:

$$A_{\mathrm{c}}\cos[2\pi n f_{\mathrm{c}}t + n\beta_{\mathrm{f}}\sin(2\pi f_{\mathrm{m}}t)] \tag{8}$$

Obviously, multiplying the n through will not only increase the carrier frequency, but also increase β_f to $n\beta_f$. If n is large enough, you will get a wideband signal. Such a method is referred to as indirect FM modulation.

⇒ **Open the file 'armstrong.slx'**.

Look over what **'armstrong.slx'** is doing and verify it implements what was just discussed. The file is called Armstrong because this type of FM modulation is called an 'Armstrong indirect Modulator' named after the man who invented the process.

- What is the original value of β_f, and what is it changed to? **(Q7)**
- Run the Simulation. Consult your Bessel table and comment on if the final spectrum (Figure 2) matches the shape we would expect for a WB FM signal with that value of β_f? Note that the magnitude won't be identical because we made approximations in the narrowband generation, but that is okay. **(Q8)**
- Since to get a desired β_f, one must also increase the carrier frequency by the same factor n, the next stage of any practical Armstrong modulator would be to mix the FM signal down to a desired frequency. Mixing will not alter β_f. There is no activity for this point, it is just mentioned to make sure you read it.

⇒ **Close 'armstrong.slx'**.

1.3 1.3 Simple Discriminator for Demodulating FM signals

A PLL is not the only way to demodulate an FM signal. One very simple and easy way to understand the method for demodulating FM signals is to consider that taking the derivative of an FM signal will create a signal with varying amplitude that is related to the message. Differentiation, in effect, converts FM to AM signals, which can be demodulated using an envelope detector. Demodulation techniques that exploit this feature are called discriminators.

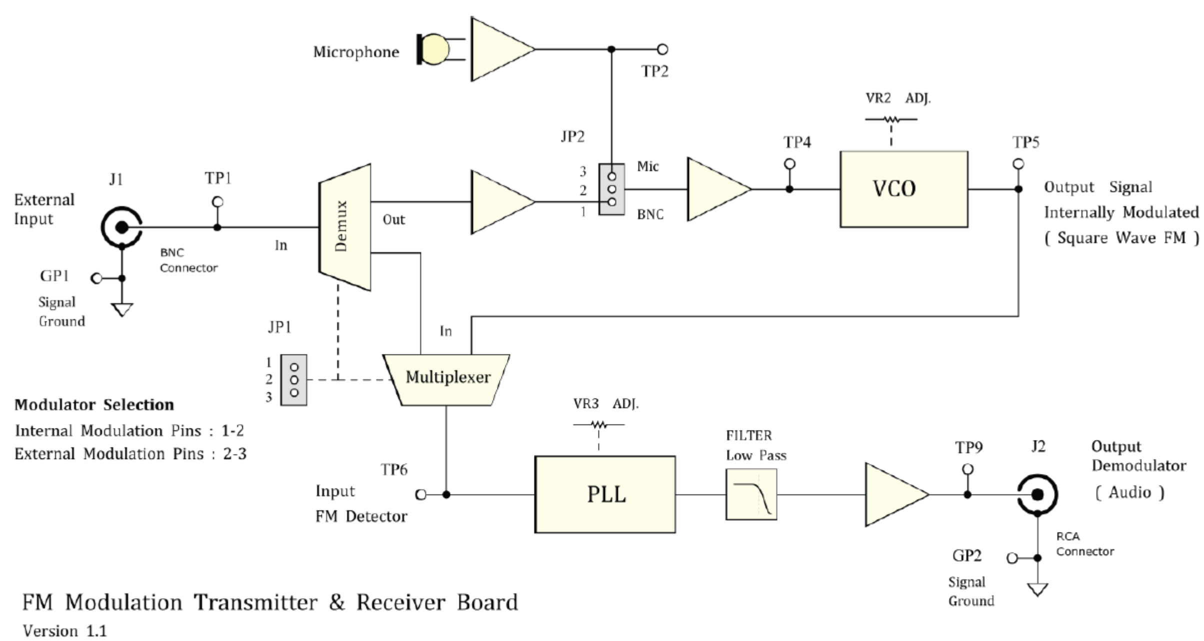
⇒ **Open the file 'fm_demod2.slx'**.

- Looking at the file, do you see how it will indeed demodulate an FM signal? Explain briefly how it works. **(Q9)**
- Run the Simulation. You can see that it does indeed work, but not as well as the PLL did. That is why this type of demodulator is called a simple discriminator. In practice, more features are added to improve the output.

⇒ **Close 'fm_demod2.slx'**.

2 FM Hardware Modulation and Demodulation

Below is the block diagram of the FM Modulation Tx-Rx (Mod/Demod) board along with a list of the signal selection jumpers and connectors.



FM Modulation Tx - Rx Board

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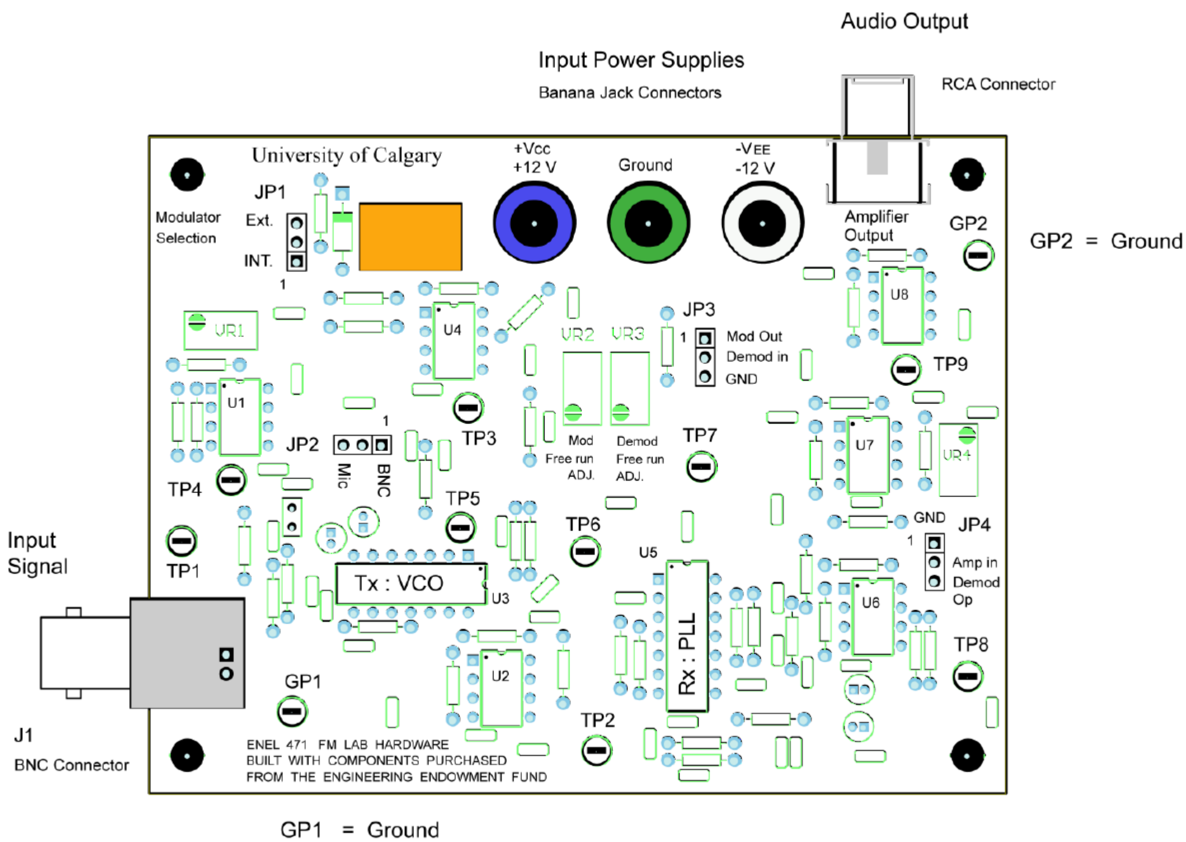
Top View - Version 1.1
Enhanced Component View 2
FM : Tx + Rx Printed Circuit Board



FM Modulation Tx-Rx board Signal Selection Jumpers Pins/Switches and Connectors.

- JP1 Pins 1 & 2 connected, selects Internal FM modulation mode with output Mod signal VCO modulator multiplexed to the demodulator PLL circuit. The input message signal can then be selected from connector (J1) or the microphone as the input to the VCO modulator. Pins 2 & 3 connected, selects External FM modulation mode. The input modulated carrier signal connected to (J1) is routed to the PLL demodulator
- JP2 Pins 1 & 2 connected, selects the message signal connector (J1) BNC as input to the VCO modulator. Pins 2 & 3 connected, selects the on board Microphone as input to VCO modulator

The FM board has two PLL chips on it. The first chip is configured as an open loop, meaning that the error voltage is not fed back as the input to the VCO. The reason for this is because the first chip is used for direct FM modulation, i.e., we only need/want to use the VCO part of it. In other words, the first PLL chip is essentially just a VCO to us.

The second PLL chip is configured like the PLL you used in the simulations and it is used to demodulate FM signals. The board has been designed so that by moving the signal selection jumpers around, it can be set-up to either:

1. Receive an already modulated FM signal (external modulation) and then demodulating it using the PLL, or
2. Receive an un-modulated message which will get internally modulated (using the VCO) and then demodulating it using the PLL.

When you are providing the FM board with an un-modulated message, another jumper controls whether the message comes from the BNC connector or the microphone. The VCOs natural frequency is 200 kHz and it outputs square waves, not sinusoids! You will see this still allows for the mod/demod to work. In real-life it would be more a problem because the square-wave carrier would have a very wide spectrum (Theoretically infinite!).

2.1 Using the AWG to output an FM signal and Demodulating it with the FM Board

Setup the Power Supply Sources:.

* **Caution:** Setup DC Power supply before you connect and power up the FM Tx-Rx board:

1. Configure the DC Power Supply: Hewlett Packard 3631A - Tripple output
   - Turn on the power, select function output On/Off to Off. This will put the power supply into standby mode (no power on the output terminals).
2. Set Power Supply voltage limits to +12V and -12V, respectively, for the two outputs:
   - Select function +25 V range button, and select button Display Limit.
   - Select adjust Voltage/Current button if necessary to set voltage adjust mode.
   - Now adjust supply for +12 Volts using position arrows and Jog shuttle wheel.
   - Select function -25 V range button, and repeat adjustments for supply -12 Volts.
3. Set Power Supply output current limits to 100 mA for each supply:
   - Select function +25 V range button and select button Display Limit.
   - Use adjust Voltage/Current button to set current adjust mode.
   - Now adjust supply output current using position arrows and Jog shuttle wheel.
   - Select function -25 V range button. Repeat current adjustments for supply range.
4. If you are unsure that you have set the voltages correctly, check the voltage outputs using the multimeter and activate the power supply output On/Off to On mode.
5. Carefully connect power supplies to the FM Board banana jack connectors:
   - Using a banana plug lead, connected to the +12V power supply to the FM Board top left socket connector labelled +Vcc, +12V.
   - The common wire (ground) goes to the top center socket connector labeled GND (ground).
   - Using a banana plug lead, connected to the -12V power supply to the FM Board the top right socket connector labeled -VEE, -12V.
6. Activate power to FM Board by selecting output On from the power supply.

Create the FM Modulating signal:

1. Turn on the Arbitrary Wave Generator (AWG)
2. Set AWG to output a sinusoidal FM signal:

- Select buttons Shift and FM.
- Set the amplitude to 4 V_{pp}.
- Select button Freq and enter 200 kHz (this is the carrier frequency).
- Select buttons Shift and Freq and enter 300 Hz (this is the message frequency).
- Select buttons Shift and Level and enter 2 kHz (this is peak frequency deviation).

View the FM signal:

- Input the signal from the AWG output into one of the oscilloscope channels with FFT capabilities.
- View the modulating carrier in the time domain and frequency domain.
- Adjust the horizontal time division knob for approximately 20 μsec.

Setup the FFT function on the oscilloscope:

- Press the 'Math' Button on the scope.
- Select 'Operator' to FFT using configuration buttons below the oscilloscope screen corresponding to software menus displayed on the scope.
- Using the 'Time/Div' (Horizontal) knob of the oscilloscope, set the FFT sample rate to 20 MSa/sec.
- Select buttons underneath the screen menus and use the multipurpose knob labeled with the lighted turning arrow, set the center frequency to 200 kHz and the Span to 10 kHz.
- **Note:** On the scope screen, a center frequency indicator triangle (orange color) is positioned on the border of the grid frame, top middle area.
- Looking at the frequency domain, what is the approximate BW? Show that this agrees with Carson's Rule. **(Ql0)**
- Input the signal from the AWG into the input BNC on the FM board and set the FM board jumpers up for external modulation. Set JP1 on pins 2 & 3.
- Look at the time domain signal at TP9 (test point 9 on the board). This is the demodulated signal.
- Did the board's PLL demodulate it correctly? Note whether it has high frequency noise or not. **(Q11)**

2.2 Using the AWG to Output a Message Signal and Demodulating it with the FM Board

On the AWG, turn the FM modulation off

- Select buttons 'Shift' and 'FM'.

The AWG is now outputting a simple sinusoid

- Set the amplitude to 1 V_{pp}.
- Set the frequency to 10 KHz.
- Select the FM board signal jumper, JP1 for Internal modulation mode.
- Select the FM board signal jumper, JP2 for input message signal, J1 connector.
- Connect the AWG to the J1 connector using the BNC cable.

View the modulating carrier in the frequency domain:

- Using an oscilloscope with FFT capabilities, view the spectrum at TP5. This is the output of the internal FM modulator (VCO).
- Setup the FFT operation as before with following parameters.
  - Sampling rate: 50 MSa/sec.
  - center frequency: 200 kHz.
  - Span: 500 kHz.
- Looking at the square wave FM spectrum, describe what happens to it as you slowly lower the message frequency from 10 kHz to 1 kHz. **(Q12)**
- With the message at 1 kHz, show calculations for determining β_{f} based on what you see on the FFT scope. **(Q13)**
- Now look at the time-domain signal on TP9 (the demodulated output). Did the PLL demodulate it correctly? How does the quality of this demodulated signal compare to the quality of the first one? Can you think of why? **(Q14)**

Create the message signal using a Microphone:

- Select the FM board signal jumper, JP2, for input Microphone message signal.

View the modulating carrier in the frequency domain:

- Using an oscilloscope with FFT capabilities, view the spectrum at TP5.
- Setup the FFT operation as before with following parameters.
  - Sampling rate: 200 MSa/sec.
  - center frequency: 200 kHz.
  - Span: 500 kHz.
- Call a TA over and show them what you do to the microphone to make the spectrum on scope get wider.
- Get a signature. **(Q15)**

Done! Hand in your answer sheet to a TA and Go!

Part 2

Lab 4 Questions

Answer the following questions. Write down the names and ID # of the group members and hand in the answer sheets to the TAs before you leave the lab.

Simulation (Simulink) Questions:

FM Demodulator 1: fm_demodl.slx

Q1 From the initial values of the parameters in the "message signal" and "VCO" blocks, determine the value of β_f?

Q2 Sketch the spectrum, for β_f and the initial message frequency. To do this, use the Bessel function table and label the magnitudes and locations of the delta functions. Does this match the spectrum from Simulink simulation?

Q3 For loop gain equal to 1, Look at the time-domain 'error voltage' scope.

- i What do you see? Is it what you expected?
- ii What is the approximate response time (the time it takes to reach steady state)?

Q4

- i What do you notice about the error voltage response to the pulse train input when it steps up?
- ii What is the approximate response time (the time it takes to reach steady state)?

Q5 In lab #3 you saw how changing the loop gain affected response time. Change the gain from 1 to 2 and observe the error voltage response to the impulse pulse train, which gain produces a faster response?

Immunity to non-linearity: immunity.slx

Q6 An AM and an FM signal are each passed through a nonlinear device followed by a BPF. Comparing the input and the output spectra of the nonlinear device.

- i Is AM immune to nonlinearity? Why or why not?
- ii Is FM immune to nonlinearity? Why or why not?

Indirect FM: 'Armstrong.slx'

Q7 i What is the value of β_f for the narrowband FM?

ii What is the value of β_f for the resulting wideband FM?

Q8 Run the simulation. Consult your Bessel function table and comment on whether the final spectrum (fig2) matches the shape we would expect for a WB FM signal with that value of β_f? Note that the magnitude won't be identical because we made approximations in the narrowband generation, but that is okay.

FM Demodulator 2: fm_demod2.slx

Q9 i Looking at the file, do you see how it will indeed demodulate an FM signal?

ii Explain briefly how it works.

Hardware Lab

Q10 i What is the approximate BW?

ii Calculate and show that this approximately agrees with Carson's Rule.

Q11 i Did the board's PLL demodulate it correctly?

ii Does it have high frequency noise or not?

Q12 Looking at the square wave FM spectrum, describe what happens to it as you slowly lower the message frequency from 10 kHz to 1 kHz?

Q13 With the message at 1 kHz, show calculations for determining β_f based on what you see on the FFT scope.

Q14 Now, look at the time-domain signal on TP9 (the demodulated output).

i Did the PLL demodulate it correctly?

ii How does the quality of this demodulated signal compare to the quality of the first one?

iii Can you think of why?

Q15 Call a TA over and show them what you do to the microphone to make the spectrum on scope get wider. Get a signature.

This is the end of ENEL 471 Labs! Good luck with the Finals!