

EECS 216 Winter 2008  
Lab 2: FM Detector  
Part II: In-Lab & Post-Lab Assignment  
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## 1 Background

### **DIGITAL vs. ANALOG communication.**

Over the past fifty years, there has been a transition from analog to digital communication systems. An analog communication system, such as AM radio (which you'll be building and charactering in Lab 3), transmits an analog signal, i.e., a signal that is continuous in time and continuous in amplitude, from the sender to the receiver. In a digital communication system, which is the focus of Lab 2, a sequence of symbols, drawn from an alphabet of finite size, is transmitted. Each symbol is sent during some fixed interval of time. The smaller this interval of time, the more symbols can be sent. You may be familiar the unit *Mbps*, which stands for *megabits per second*, as a measure of performance in computer networks. These networks are examples of digital communication systems, where the alphabet consists of *binary digits*, or *bits*, also better known as the symbols 0 and 1. Note that this so-called *binary* alphabet is as small as any alphabet can get without becoming meaningless.

Digital communication systems have a number of advantages relative to analog ones. First, in today's world, much of the information we wish to transmit is already in digital form. Second, it is easy to store and process digital data. Third, it is possible to detect and correct errors in digital communication in ways that are impossible in analog communication. Finally, multiple digital data streams may be easily multiplexed and sent together. If you wish to learn more about digital communications, you should take EECS 455.

**Converting analog signals into digital signals.** Just because a signal is analog doesn't mean it can't be transmitted digitally. Any analog signal can be converted into a digital one by taking samples (i.e., sampling) of the analog signal at uniformly spaced instants in time and converting the sample values into binary numbers (i.e., quantization). In CD-quality audio, for example, each audio sample is represented by 16 bits, whereas, in today's consumer digital cameras, 12 bits are used to code each color. Once in binary form, each signal value can be transmitted as a sequence of bits.

**Your Lab 2 Goal.** Once in digital form, there are many different ways, known as modulations, to transmit digital data. One common modulation is known as frequency shift keying (FSK). In M-ary FSK the data is transmitted as a sequence of tones (i.e., sinusoids), where each tone can have only one of M possible frequencies. In this Lab, we will consider binary (i.e, M=2) FSK where only two frequencies are possible. The higher frequency tone will be assigned the binary digit 1, while the lower frequency tone will be assigned the binary digit 0. The PC on your lab bench has been loaded with a secret message (i.e., a base 10 number between 0 and 255), and this number has been converted into its corresponding 8 bit binary string. For example the number 34 would be converted into the string 00100010. The computer will transmit this 8-bit binary string using a sequence of 8 binary FSK symbols each of 100 ms duration. You will use the output of your frequency discriminator to determine the frequency of these eight tones. From these frequencies you will reconstruct the 8-bit binary string and the corresponding secret base 10 number (which lies between 0 and 255).

**What you'll need to achieve your goal.** Since the message is encoded as a sequence of tone bursts of differing frequencies, you're going to need a circuit that converts the input signal (100-ms sinusoids) into an output signal that reflects the frequency of each sinusoid. This is the idea behind a *frequency discriminator*. You'll use a differentiator to filter the input signal so that the amplitude of the filter output will vary as

a function of the frequency of the sinusoidal input. Then, you'll extract the *envelope* of the signal, which will eliminate the temporal fine structure of the signals leaving only the slowly-varying amplitudes of the sinusoids. In this form, you'll be able to read the 0 bit, whenever the amplitude is low, and the 1 bit, whenever the amplitude is high.

## 2 Laboratory Work

Unless otherwise specified, it will be assumed that the unit of time is the second and the unit of voltage is the Volt. **Make certain that the oscilloscope is set for DC coupling for all of these measurements.**

### 2.1 Construct Frequency Discriminator Circuit

The figure below shows a diagram of the frequency-discriminator circuit.

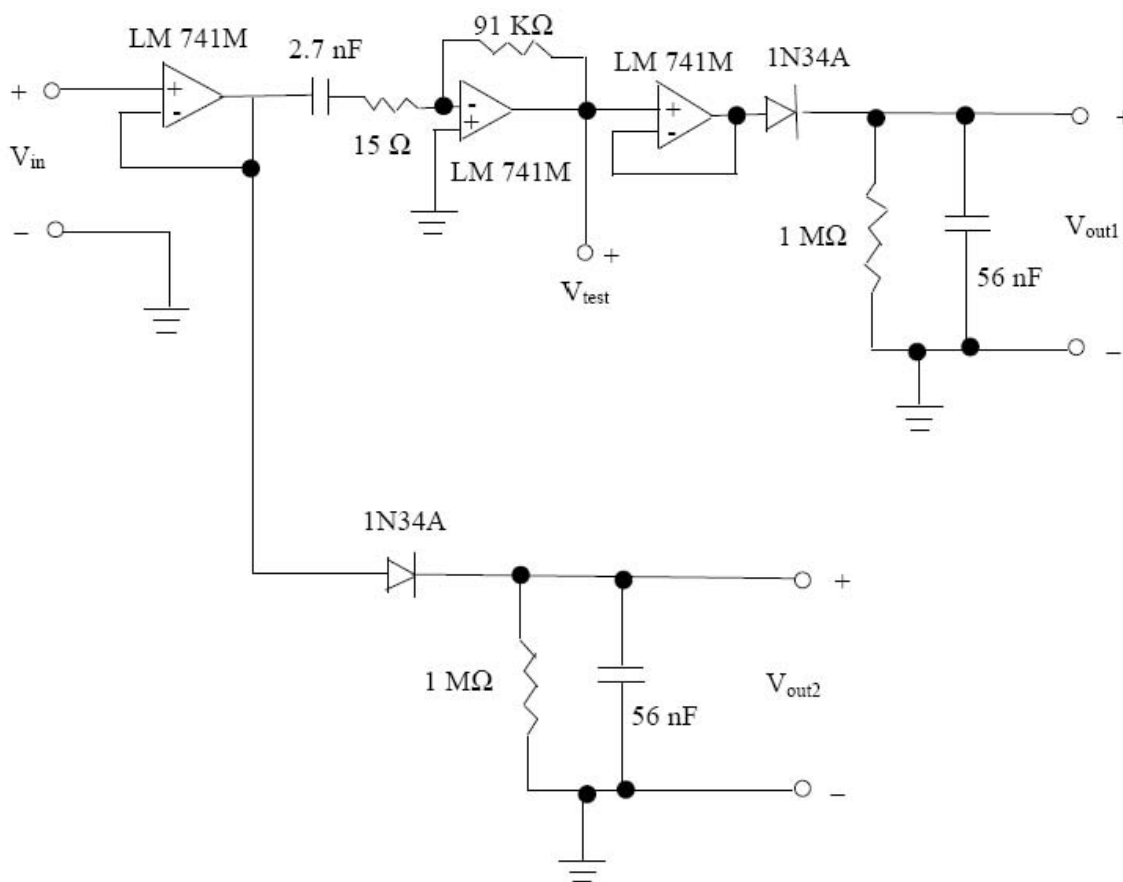


Figure 2.1.1: Frequency Discrimination Circuit

#### Parts List for Lab 2:

Resistors	Capacitors	Other components
2 1MΩ	2 56nF	
1 91 KΩ	1 2.7nF	3 op-amps (LM 741 M)
1 15 Ω	2 1 μF (for op-amp power supply lines)	2 diodes (1N34A)

The frequency-discriminator consists of two major components a differentiator (see Fig. 4.3.1 in the Pre-Lab) and (two) envelope detectors (see Fig. 3.5.3 in the Pre-Lab). It also contains two op-amp voltage-follower circuits (see Fig. 2.1.2) shown below. These voltage-follower circuits present a high impedance at their inputs and thus do not load any source or circuit to which they are connected. Thus, they can be used to connect circuit elements so that the responses of the individual circuit elements do not affect one another. (The voltage-follower circuit gets its name by applying the Golden Rules of op-amp operation, whereby  $V_o = V_i$ .)

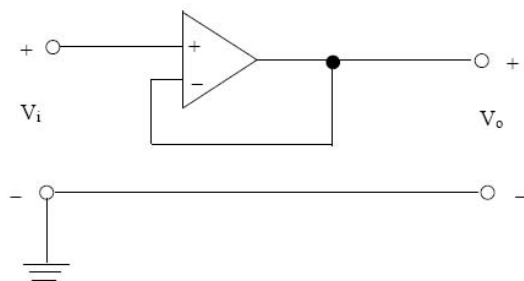


Figure 2.1.2: Op-amp Voltage-Follower Circuit

You learned about op-amps in EECS 215, and you can find the details about op-amp operation in your EECS 215 lab book. For convenience the pin layout of the LM 741 opamp is repeated below.

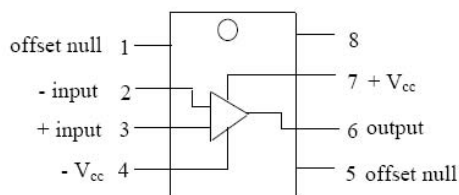


Figure 2.1.3: Pin Layout for LM 741 Op-Amp

Pins 7 and 4 are the plus and minus power supply connections, respectively, while pins 3 and 2 are the non-inverting and inverting inputs, respectively. Pin 7 should be connected to +12 V and pin 4 to -12 V. Pins 1, 5 and 8 will not be used.

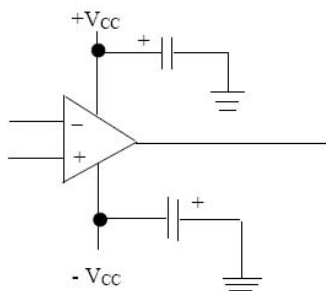


Figure 2.1.4: Op-Amp Power Supply Connections

To suppress oscillations place a  $1 \mu F$  capacitor between each power supply rail and ground.

**Your Task.** Your GSI has constructed the frequency discriminator circuit shown in Fig. 2.1.1 except that he or she has removed four of the components. You will find these components next to the board. The circuit has been reproduced in the first section of the Post-Lab. On that diagram, circle which components are missing. Then, complete the circuit by inserting the four components in their proper location. Once you have done so, have your GSI check your work. They should sign off on the circuit diagram in Section 4.1 before you go on to the rest of the lab.

## 2.2 Differentiator

Consider the general form of a differentiator circuit shown in the preceding section and repeated below in Fig. 2.2.1. In our particular case,  $R_1 = 15\Omega$ ,  $R_f = 91\text{k}\Omega$  and  $C = 2.7\text{nF}$ . In the following, you will characterize the behavior of this circuit with respect to several types of signals.

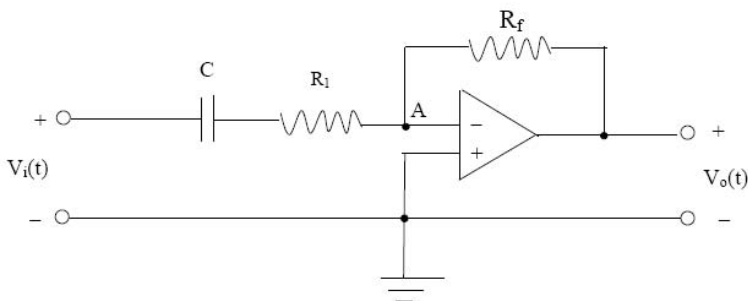


Figure 2.2.1: Operational Amplifier Differentiator Circuit

**Your Tasks.** Complete the following tasks and use your work to complete the Post-lab assignment. For many of the tasks, specialized hints or instructions are provided in *italics*. Save yourself time: read and follow these hints or instructions.

- (a) (i) Connect your signal generator to the input denoted  $V_{in}$  and connect your scope between  $V_{test}$  and ground (see Fig. 2.1.1). [*Important note: When making these measurements it is necessary to avoid saturating the operational amplifier, and thus the op-amp output voltage must be less than the applied power supply voltage. To be on the safe side, set the input signal amplitude so that the op-amp output signal level does not exceed  $\pm 5$  V.*]

Use your signal generator and oscilloscope to measure the frequency response,

$$H(j2\pi f) = \frac{V_{test}(j2\pi f)}{V_{in}(j2\pi f)}$$

at the following frequencies:  $f = 100$  Hz, 500 Hz, 1 KHz, 2 KHz and 5 KHz.

Record your data for future use in the postlab in the Table below.

[*Note that  $H(j2\pi f)$  is a complex number, and hence it has a magnitude,  $|H(j2\pi f)|$ , and a phase,  $\angle H(j2\pi f)$ .  $|H(j2\pi f)|$  is given by the ratio of the amplitude of the sinusoid at the output (i.e.,  $V_{test}$ ) of the circuit to the amplitude of the sinusoid applied to the input (i.e.,  $V_{in}$ ) of the circuit.  $\angle H(j2\pi f)$  is the phase difference between these output and the input sinusoidal waveforms. Similar frequency transfer function measurements were done in Lab 1 (see sections 4.7 and 5.6 of Lab 1).*]

- (ii) Using the data you collected in part (i), make a table of  $|H(j2\pi f)|$  and  $\angle H(j2\pi f)$  (in degrees) vs.  $f$ . Note: Your answers should be in (reasonable) agreement with your prelab calculations for the ideal differentiator.

Frequency [Hz]	$V_{in}$ pk-pk	$V_{out}$ pk-pk	Delay ( $\Delta t$ )

Table 2.2.1: Measured input-output characteristics of the differentiator circuit.

(b) Use the signal generator to generate a sinc waveform,

$$V_i(t) = A \operatorname{sinc}(\alpha t) = A \frac{\sin(\pi \alpha t)}{\pi \alpha t} \text{ V} \quad (2.2.1)$$

Keeping all of the circuit connections the same as in part (i) above, apply this waveform to the circuit and record the measured data (and a plot of this data) on the lab computer.

[The sinc function can be generated by pushing the following sequence of buttons on the signal generator: Arb, select wform, built-in, sinc. Set the amplitude  $A$  to 3 Vpp, the frequency ( $f$ ) to 100 Hz (note: the signal generator sets  $\alpha$  equal to  $40 \times f$ ) and the offset to 0 V.]

## 2.3 Fourier Series

Keeping all your connections the same as in Section 2.2, use your signal generator to apply the following periodic input to the circuit.

$$V_i(t) = \begin{cases} 4 \left(1 - \frac{|t|}{a}\right) - 2 \text{ V}, & |t| \leq a \\ 4 \left(\frac{|t|}{a} - 1\right) - 2, & a < |t| \leq T \end{cases} \quad (2.3.1)$$

where  $a = T/2 = 5$  ms. [Note that this waveform can be realized using the ramp function of the signal generator with the following parameter settings: amplitude = 4 Vpp, 0 V offset, period = 10 ms and symmetry = 50%.]

**Your Task.** Record the measured output data (and a plot of this data) on the lab computer. Comment: Since the operation of this circuit component is *approximately* a differentiator (i.e.,  $V_{test}(t) = -b \frac{dV_i(t)}{dt}$ ), you should be able to anticipate the general form of the output.

## 2.4 Envelope Detector

Place a 1 K $\Omega$  resistor in series with a 1N34A pn junction diode as shown below.

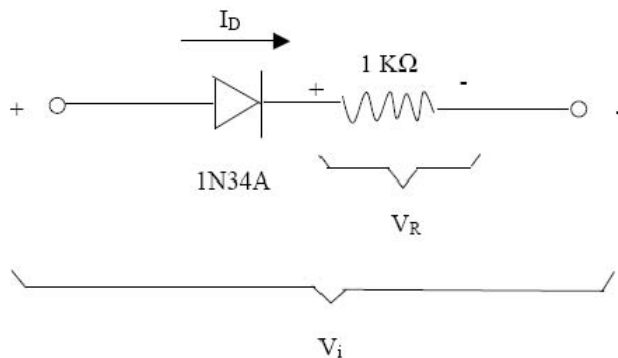


Figure 2.4.1: pn junction diode

$V_{in}$ (V)	$V_R$ (V)	$V_D$ (V)	$I_D$ (mA)	$R_D$ ( $\Omega$ )
-2				
-1				
-0.5				
0.1				
0.5				
1				
2				

Table 2.4.1: pn junction diode characteristics

**Your Tasks.**

- (a) Apply the following DC voltages,  $V_{in}$ , across the series combination of the diode and resistor:

$$-2 \text{ V}, -1 \text{ V}, -0.5 \text{ V}, 0.1 \text{ V}, 0.5 \text{ V}, 1 \text{ V}, 2 \text{ V}$$

and measure the corresponding voltage  $V_R$ . Use this data to fill in the second column of the table shown below.

- (b) Connect the signal generator to channel 1 of the scope and to the input (i.e.,  $V_{in}$ ) of the circuit shown in Fig. 2.1.1.

Connect channel 2 of the oscilloscope to the output  $V_{out2}$ .

Set the signal generator to 50  $\Omega$  load instead of high Z using the utility menu on the signal generator.

Use the AM modulation function of the signal generator to produce the following waveform

$$V_i(t) = (5 + 2 \sin(2\pi f_m t)) \sin(2\pi f_c t) \text{ V}$$

Observe the waveforms that appear on the scope (both channels 1 and 2) when  $f_c = 1$  KHz and  $f_m = 10$  Hz. Record the measured outputs (and plots of this data) on the lab computer. Repeat your measurements for  $f_c = 200$  Hz,  $f_m = 10$  Hz.

Finally, repeat your measurements when the input waveform is

$$V_i(t) = (2.5 + x(t)) \sin(2\pi f_c t) \text{ V}$$

where  $x(t)$  is a triangular wave with frequency 10 Hz and peak-to-peak amplitude 2 V, and  $f_c = 1$  KHz. Your GSI will come by your lab bench to view these plots before you leave the lab.

[Notes: The signal generator is able to produce amplitude-modulated signals of the form

$$V_i(t) = (A + x(t)) \sin(2\pi f_c t)$$

$f_c$  is called the carrier frequency,  $2A$  is the peak-to-peak amplitude of the carrier and  $x(t)$  the modulating signal. Use the following sequence to set-up the signal generator: Press the sin function button on the signal generator in order to set the peak-to-peak carrier amplitude and carrier frequency. Use the menu that appears, to set the values for  $f_c$  (carrier frequency) and  $2A$  (carrier amplitude p-p). Set the offset to 0 V. Press the modulation button to specify (using the menu that appears) the modulating signal  $x(t)$ , which in this problem is either a sinusoid or a triangular wave. Specify the frequency,  $f_m$ , of the modulating signal and the modulation depth, where

$$\text{modulation depth} = \frac{\max(x(t)) - \min(x(t))}{2A} \times 100\% \quad (2.4.1)$$

Thus, if

$$V_i(t) = (5 + 2 \sin(2\pi f_m t)) \sin(2\pi f_c t) \text{ V}$$

the peak-to-peak carrier amplitude is 10 V and the modulation depth is  $\frac{2 - (-2)}{2(5)} \times 100\% = 40\%$ .]

## 2.5 Frequency Discriminator

Make sure that the signal generator is set to high  $Z$  mode using the utility menu on the signal generator.

### Your Tasks.

Keeping the same connections used in Section 2.4, set the signal generator output to be a 5 V p-p sinusoid at a frequency of  $f = 1$  KHz. Observe the outputs  $V_{out1}$  and  $V_{out2}$  on the scope. These outputs should be DC signals, i.e., nearly constant voltages with respect to time. Record the measured outputs (and a plot of this data) on the lab computer. Compute and record the quantity

$$\frac{1}{2\pi(R_d C_d)} \frac{V_{out1} + 0.25}{V_{out2} + 0.25}$$

where  $C_d = 2.7$  nF and  $R_d = 91$  k $\Omega$ .

Repeat with an input sinusoid at a frequency of  $f = 2$  KHz with a peak-to-peak of 5 V.

Your GSI will come to your lab bench and he/she will set your signal generator to a “secret” frequency and voltage. You will be asked to determine this frequency using your frequency discriminator circuit. [*Hint: Suppose that  $V_i(t) = A \sin(\omega t)$  in Fig. 2.1.1. Compute the voltages  $V_{test}(t)$ ,  $V_{out1}(t)$  and  $V_{out2}(t)$ . What should*

$$\frac{1}{2\pi(R_d C_d)} \frac{V_{out1} + 0.25}{V_{out2} + 0.25}$$

*equal? A small offset voltage (i.e., 0.25 V) has been added to  $V_{out1}$  and  $V_{out2}$  in the equation above to compensate for the small voltage drop across the forward-biased germanium pn junction diode.]*

**Your GSI will look at your stored plots for the in-lab portion of Lab 2 before you leave the lab. He/she will determine whether you completed the lab successfully, and he/she will record this information as part of your final lab grade.**

## 2.6 Frequency Discrimination To Decode Frequency-Shift Keying Message

Having characterized the major components of the frequency-discrimination circuit, you’re now ready to examine its use in digital communication. You will use your frequency discriminator to decode a secret message that has been encoded using Frequency-Shift Keying (FSK). Specifically, this secret message is encoded in *binary* FSK and your task is to determine the frequencies used to represent the 0 and 1 bits and what the binary message is in our standard base-10 system.

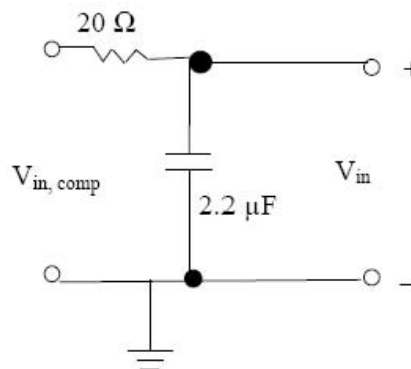


Figure 2.6.1: Low-pass filter before input of frequency discriminator;  $V_{in,comp}$  will come from the headphone jack and  $V_{in}$  is the same as shown in Fig. 2.1.1

Next, set-up the simple low-pass filter, as shown in Fig. 2.6.1, so that the output of the filter is connected to  $V_{in}$ , as shown in Fig. 2.1.1. This low pass filter is necessary to eliminate some high frequency noise that

	Measured $V_{out1}$ (V)	Measured $V_{out2}$ (V)	Computed $\frac{1}{2\pi(R_d C_d)} \frac{V_{out1} + 0.25}{V_{out2} + 0.25}$ (Hz)	freq.
High frequency, '1'				
Low frequency, '0'				

Table 2.6.1: Calculating the high and low frequencies, used to indicate the bits 1 and 0

Bit	1	2	3	4	5	6	7	8
Base-10 number	128	64	32	16	8	4	2	1
'1' or '0'								

Table 2.6.2: Decoding FSK Message

will come from the computer input to the system, but will not have a significant effect on the frequencies of the FSK message.

Launch Windows Media Player (WMP) and open the file on the Desktop titled `test.FSK.binary.wav`. On your lab bench, you will find a headphone plug that terminates in two long wires, a signal and a ground. Put the plug into the computer's headphone jack and connect the wires across  $V_{in,comp}$  shown in Fig 2.6.1. Before decoding the FSK message, you can hear what it sounds like by connecting the speaker at your lab bench to  $V_{in,comp}$  and playing the file in WMP. The file is very short (0.8s), so you may want to play it a couple of times to get a feel for what it sounds like.

Now you are ready to decode the message, but be sure to first disconnect the speaker before you do because it draws a lot of the signal power which makes it harder to accurately decode the signal.

**Your Task.** Leave all of your connections to the scope the same ( $V_{out1}$  to Ch1,  $V_{out2}$  to Ch2). The FSK message consists of 8 bits, each of which is transmitted for a fixed duration. You should adjust the time-scale of the scope so that you can see the entire message. Set the trigger to: Edge, Ch1, upward slope, Normal, DC, with a trigger level around 100 mV.

Play the file `test.FSK.binary.wav`, and once the scope has captured the message, hit Stop so you can perform analysis on it.

Determine the high and low frequencies, associated with the '1' and '0' bits, respectively. [*Hint: Remember that the frequency is given by*

$$\frac{1}{2\pi(R_d C_d)} \frac{V_{out1} + 0.25}{V_{out2} + 0.25} \text{ Hz},$$

*which means that the higher frequency will be associated with the higher value of  $V_{out1}$  and corresponding value of  $V_{out2}$ , and the lower frequency will be associated with the lower value of  $V_{out1}$  and corresponding value of  $V_{out2}$ .*

Use the cursors to measure the voltage levels for each channel, and fill out Table 3.6.1 to turn in with your post-lab. If you perform your calculation correctly, your high frequency should be approximately two times your low frequency, as is common with FSK transmission.

Now decode the message, reading from left to right, to fill out Table 3.6.2 and turn it in with your post-lab. Recall that the message is 8 bits long and each bit is 100ms so you can recognize repeated bits.

After filling out Table 3.6.2, add up all of the base-10 numbers associated with a 1 bit to get the secret numerical message, which you'll report in your post-lab. Check with your lab GSI to make sure you've gotten the correct answer.



### 3 Post-Lab Assignment

#### 3.1 Circuit-board layout

In the diagram below, circle the four components that are missing in the circuit board that you were provided at the beginning of the lab.

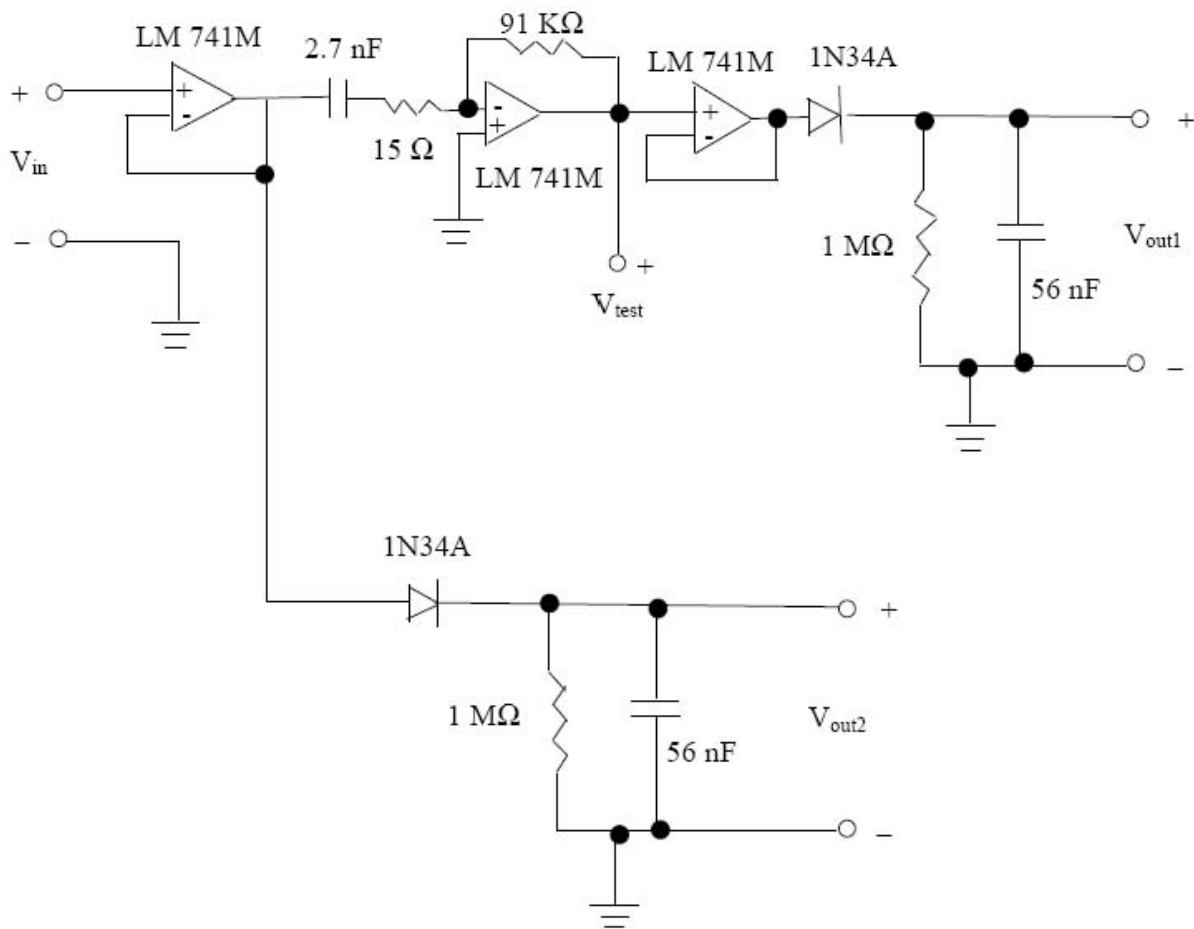


Figure 3.1.1: Frequency Discrimination Circuit

### 3.2 Differentiator

- (a) Prepare a table (see below) that compares the frequency transfer function measurements made in lab Section 2.2 with the corresponding pre-lab calculations made in pre-lab Section 4.3 (b).

Frequency (Hz)	$ H(j2\pi f) $ (measured)	$ H(j2\pi f) $ (computed)	$\angle H(j2\pi f)$ (deg) (measured)	$\angle H(j2\pi f)$ (deg) (computed)

Table 3.2.1: Comparison of Measured and Computed Frequency Transfer Function

- (b) Using Matlab, plot on a single graph the circuit response measured in lab Section 2.2(b) together with the calculated response,  $-b \frac{d}{dt} \left( A \frac{\sin(\pi\alpha t)}{\pi\alpha t} \right)$ , where  $b = (91\text{k}\Omega)(2.7\text{nF}) = 2.46 \times 10^{-4}$  and  $\alpha = 4000\text{s}^{-1}$ . For your graph use the Matlab axis command `axis([ -0.005 0.005 -5 5 ])`. Note:

$$-b \frac{d}{dt} \left( A \frac{\sin(\pi\alpha t)}{\pi\alpha t} \right) = \frac{b}{\pi a} \frac{\sin(\pi\alpha t) - \pi\alpha t \cos(\pi\alpha t)}{t^2}$$

Both the numerator and denominator in the above expression approach zero as  $t$  approaches zero. The limit, however, as  $t$  approaches zero exists and is equal to zero.

### 3.3 Fourier Series

Using Matlab plot on a single graph the circuit response measured in lab Section 2.3 together with the calculated response (i.e.,  $-b \frac{d}{dt}$ (input), where  $b = (91\text{k}\Omega)(2.7\text{nF})$ ). For your graph use the Matlab axis command `axis([ -0.025 0.025 -0.8 0.8 ])`. You will notice that the measured data contains a lot of “ringing.” See if you can explain this ringing phenomena in two or three sentences.

### 3.4 Envelope Detector

- (a) Using the data collected in in-lab Section 2.4, complete the following table. Your solution should be based on using  $R = 1.1\text{k}\Omega$ . Let  $V_D$  be the voltage drop across the diode and  $R_D$  be the diode resistance.

$V_{in}$ (V)	$V_R$ (V)	$V_D$ (V)	$I_D$ (mA)	$R_D$ ( $\Omega$ )
-2				
-1				
-0.5				
0.1				
0.5				
1				
2				

Table 3.4.1: pn junction diode characteristics

- (b) Turn in the plots collected and stored in Section 2.4 (b): signal is at 10 Hz for all three, for 1) carrier is 10Vpp, 1kHz and signal is sine, for 2) carrier is 10Vpp, 200 Hz and signal is sine, and for 3) carrier is 5Vpp, 1kHz and signal is triangle.

### 3.5 Frequency Discriminator

Using the data collected in in-lab Section 2.5 complete the following table where  $R_d = 91 \text{ K}\Omega$  and  $C_d = 2.7 \text{ nF}$ .

Signal generator freq. (Hz)	Signal generator voltage (V p-p)	Measured $V_{out1}$ (V)	Measured $V_{out2}$ (V)	Computed freq. $\frac{1}{2\pi(R_d C_d)} \frac{V_{out1} + 0.25}{V_{out2} + 0.25}$ (Hz)
1000	5			
2000	5			

Table 3.5.1: Frequency Discriminator Measurements

Suppose the input to your discriminator circuit shown in Fig. 2.1.1 is given by  $V_i(t) = A \sin(\omega_i t + \pi/3)$  V. If  $V_{out1} = 0.5 \text{ V}$  and  $V_{out2} = 2 \text{ V}$ , find the values of  $A$  and  $\omega_i$ .

### 3.6 Frequency Discrimination To Decode Frequency-Shift Keying Message

Using the data collected in Section 2.6, fill in the following tables and note the secret FSK message.

	Measured $V_{out1}$ (V)	Measured $V_{out2}$ (V)	Computed freq. $\frac{1}{2\pi(R_d C_d)} \frac{V_{out1} + 0.25}{V_{out2} + 0.25}$ (Hz)
High frequency, '1'			
Low frequency, '0'			

Table 3.6.1: Calculating the high and low frequencies, used to indicate the bits 1 and 0

Bit	1	2	3	4	5	6	7	8
Base-10 number	128	64	32	16	8	4	2	1
'1' or '0'								

Table 3.6.2: Decoding FSK Message

Secret FSK message is: