FM Modulation and Demodulation

Goal:

The goal of this experiment is to become familiar with FM modulation and demodulation.

Theory and background:

1. FM modulation:

Frequency modulation (FM) is a process in which the carrier frequency is varied by the amplitude of the modulating signal (i.e., intelligence signal). The FM signal can be expressed by the following equation:

$$x_{FM}(t) = A_c \cos(\theta t) = A_c \cos(2\pi f_c t + 2\pi f_\Delta \int x(\lambda) d\lambda) \text{ (1)}$$

If $x(\lambda) = A_m \cos(2\pi f_m \lambda)$, then:

$$x_{FM}(t) = A_c \cos(2\pi f_c t + \beta \sin(2\pi f_m t)) \text{ (2)}$$

Where

θ (t) = instantaneous modulated frequency

f_c = carrier frequency

f_m = modulating frequency

β = modulation index = $A_m(f_\Delta/f_m)$

The frequency of FM signal $x_{FM}(t)$ may be expressed as

$$f = \frac{1}{2\pi} \frac{d}{dt} \theta(t) = f_c - f_m \beta \cos(2\pi f_m t) \text{ (3)}$$

From (3) we can find that the frequency of frequency modulated signal occurs frequency deviation from the center frequency of the carrier when the intelligence amplitude is variation.

FM Generation with VCO

The VCO - voltage controlled oscillator - is available as a low-cost integrated circuit (IC), and its performance is remarkable. The VCO IC is generally based on a bi-stable 'flip-flop', or 'multi-vibrator' type of circuit. Thus its output waveform is a rectangular wave. However, ICs are available with this converted to a sinusoid. The mean frequency of these oscillators is determined by an RC circuit.

The controllable part of the VCO is its frequency, which may be varied about a mean by an external control voltage.

The variation of frequency is remarkably linear, with respect to the control voltage, over a large percentage range of the mean frequency. This then suggests that it would be ideal as an FM generator for communications purposes.

Unfortunately such is not the case.

The relative instability of the center frequency of these VCOs renders them unacceptable for modern day communication purposes. The uncertainty of the center frequency does not give rise to problems at the receiver, which may be taught to track the drifting carrier. The problem is that spectrum regulatory authorities insist, and with good reason, that communication transmitters maintain their (mean) carrier frequencies within close limits.

It is possible to stabilize the frequency of an oscillator, relative to some fixed reference, with automatic frequency control circuitry. But in the case of a VCO which is being frequency modulated there is a conflict, with the result that the control circuitry is complex, and consequently expensive.

For applications where close frequency control is not mandatory, the VCO is used to good effect. This experiment is an introduction to the FM signal and we use VCO for generating FM signals.

Varactor Diode is plays major rule in VCO. Therefore, we are going to describe it briefly.
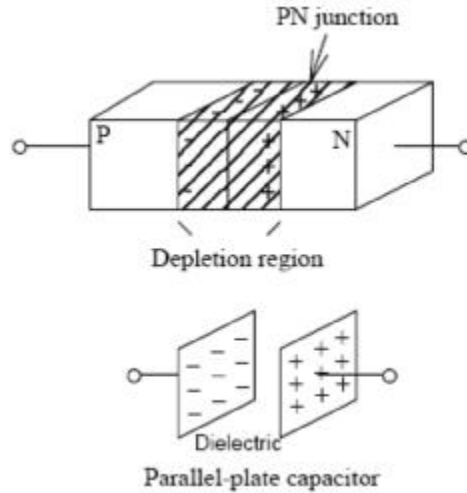
Varactor Diode

The varactor diode, sometimes called tuning diode, is the diode whose capacitance is proportional to the amount of the reverse bias voltage across p-n junction. Increasing the reverse bias voltage applied across the diode decreases the capacitance due to the depletion region width becomes wider.

Conversely, when the reverse bias voltage decreased, the depletion region width becomes narrower and the capacitance increased. When an ac voltage is applied across the diode, the capacitance varies with the change of the amplitude.

A relationship between a varactor diode and a conventional capacitor is shown in Figure 1. In fact, a reverse-biased varactor diode is similar to a capacitor.

When a p and n semiconductors combined together, a small depletion region is formed because of the diffusion of minority carriers. The positive and negative charges occupy n and p sides of junction, respectively. This just likes a capacitor. The amount of internal junction capacitance can be calculated by the capacitance formula

$$c = \frac{\varepsilon A}{d} \ (4)$$

Figure 1: Relationship between varactor diode and capacitor

From the formula above, we know that the varactor capacitance is inversely proportional to the width of depletion region (or the distance between plates) if the area A is constant. Therefore, a small reverse voltage will produce a small depletion region and a large capacitance. In other words, an increase in reverse bias will result in a large depletion region and a small capacitance.

A varactor diode can be considered as a capacitor and resistor connected in series as shown in Figure 2. The CJ is the junction capacitance between p and n junctions. The Rs is the sum of bulk resistance and contact resistance, approximately several ohms, and it is an important parameter determining the quality of varactor diode.
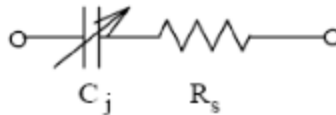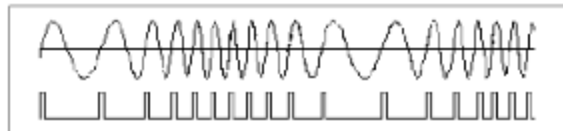

Figure 2: the equivalent circuit of varactor diode

2. FM Demodulation
   a. The zero-crossing-counter demodulator

A simple yet effective FM demodulator is one which takes a time average of the zero crossings of the FM signal. Figure 3 suggests the principle.

Figure 3: An FM signal, and a train of zero-crossing pulses

Each pulse in the pulse train is of fixed width, and is located at a zero crossing of the FM signal. This is a pulse-repetition-rate modulated signal. If the pulse train is passed through a low pass

filter, the filter will perform an averaging operation. The rate of change of this average value is related to the message frequency, and the magnitude of the change to the depth of modulation at the generator.

This zero-crossing-counter demodulator will be modeled in the latter part of the experiment and used for demodulation low frequency FM. The phase locked loop (PLL) as a demodulator will be studied in the next section.

b. FM Demodulation with the PLL

The phase locked loop is a non-linear feedback loop. To analyze its performance to any degree of accuracy is a non-trivial exercise. To illustrate it in simplified block diagram form is a simple matter. See Figure 4.
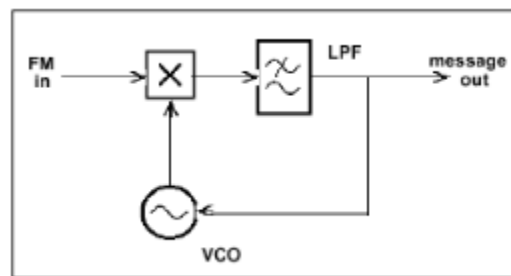

Figure 4: The basic PLL

This arrangement can be used for many purposes. For Carrier acquisition the output was taken from

the VCO. As an FM demodulator, the output is taken from the LPF, as shown. It is a simple matter to describe the principle of operation of the PLL as a demodulator, but another matter to carry out a detailed analysis of its performance. It is complicated by the fact that its performance is described by non-linear equations, the solution to which is generally a matter of approximation and compromise.

The principle of operation is simple - or so it would appear. Consider the arrangement of Figure 4 in open loop form. That is, the connection between the filter output and VCO control voltage input is broken.

Suppose there is an unmodulated carrier at the input.

The arrangement is reminiscent of a product, or multiplier-type, demodulator. If the VCO was tuned precisely to the frequency of the incoming carrier, then the output would be a DC voltage, of magnitude depending on the phase difference between itself and the incoming carrier.

For two angles within the 360 degrees range the output would be precisely zero volts DC.

Now suppose the VCO started to drift slowly off in frequency. Depending upon which way it drifted, the output voltage would be a slowly varying AC, which if slow enough looks like a varying amplitude DC. The sign of this DC voltage would depend upon the direction of drift.

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Suppose now that the loop of Figure 4 is closed. If the sign of the slowly varying DC voltage, now a VCO control voltage, is so arranged that it is in the direction to urge the VCO back to the incoming carrier frequency w_0 , then the VCO would be encouraged to 'lock on' to the incoming carrier. This is the principle of carrier acquisition.

Next suppose that the incoming carrier is frequency modulated. For a low frequency message, and small deviation, you can imagine that the VCO will endeavor to follow the incoming carrier frequency. What about wideband FM? With 'appropriate design' of the low pass filter and VCO circuitry the VCO will follow the incoming carrier for this too.

The control voltage to the VCO will endeavor to keep the VCO frequency locked to the incoming carrier, and thus will be an exact copy of the original message.

Analysis of PLL operation

The PLL is an electronic feedback control system, as illustrated by the block diagram in Figure 5, of locking the output and input signals in good agreements in both frequency and phase. In radio communication, if a carrier frequency drifts due to transmission, the PLL in receiver circuit will track the carrier frequency automatically.
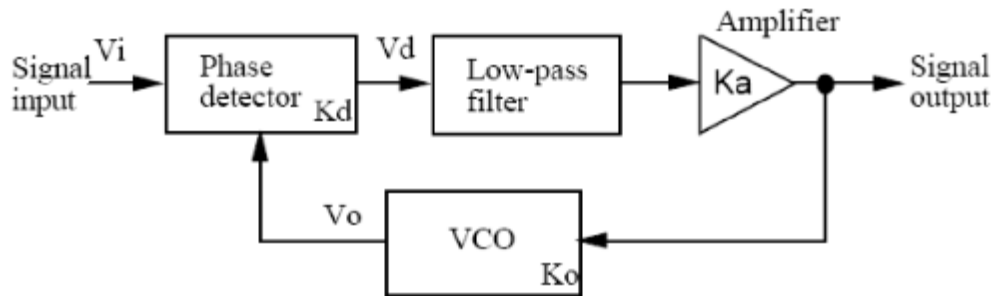
Figure 5. PLL block diagram

The PLL in the following experiments is used in two different ways: (1) as a demodulator, where it is used to follow phase or frequency modulation and (2) to track a carrier signal which may vary in frequency with time. In general, a PLL circuit includes the following sections:

1. Phase Detector (PD)

2. Low Pass Filter (LPF)

3. Voltage Controlled Oscillator (VCO)

The phase detector within the PLL locks at its two inputs and develops an output that is zero if these two input frequencies are identical. If the two input frequencies are not identical, then the output of detector, when passed through the low-pass filter removing the ac components, is a dc level applied to the VCO input. This action closes the feedback loop since the dc level applied to the VCO input changes the VCO output frequency in an attempt to make it exactly match the input frequency. If the VCO output frequency equals the input frequency, the PLL has achieved lock,
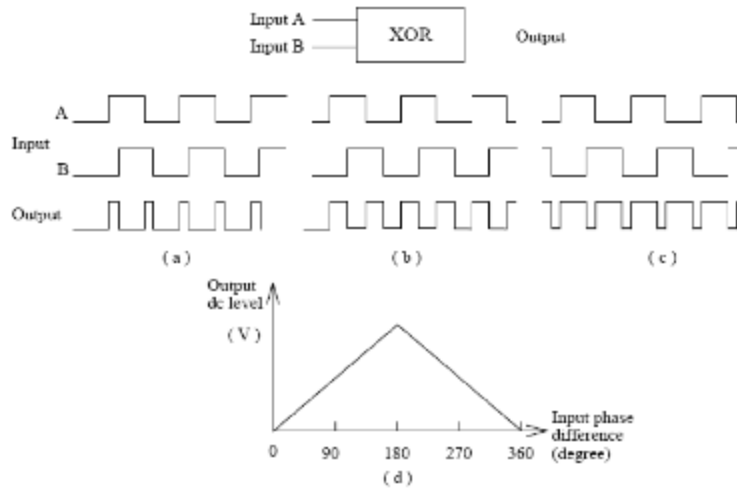
and the control voltage will be zero for as long as the PLL input frequency remains constant. The parameters of PLL shown in Figure 5 are as follows:

Kd = phase detector gain in volts/radian

Ka = amplifier gain in volt/volt

Ko = VCO gain in kHz/volt

$KL = KdKaKo$ =closed loop gain in kHz/volt

Figure 6: Phase detection

A better understanding of the operation of phase detector may be obtained by considering that the simple EXCULSIVE-OR (XOR) gate is used as a phase detector. The XOR gate can be thought of as an inequality detector which compares the inputs and produces a pulse output when these inputs are unequal. The width of the output pulse is proportional to the phase error of the input signals. As shown in Figure 6, the width of the output pulse of (b) is larger than that of (a) and is smaller than that of (c). When the output of phase detector is applied to the input of low-pass filter, the output of low-pass filter should be a dc level that is directly proportional to the pulse width. In other words, the output dc level is proportional to the phase error of input signals. Figure 6 (d) shows the relationship between the input phase error and the output dc level.
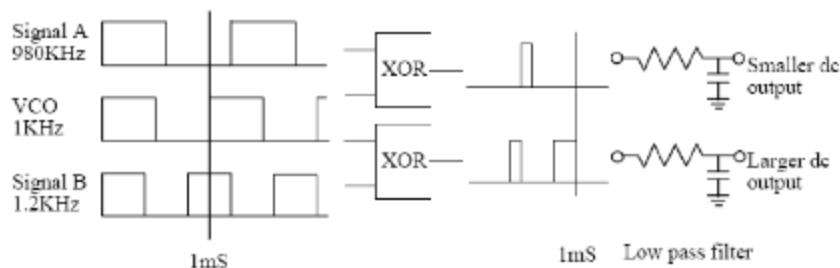
Figure 7: Operation of frequency locking

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For a further understanding of the operation of the PLL can be obtained by considering that initially the PLL is not in lock. The VCO has an input voltage of 2V and is running at its free-running frequency, say 1 kHz. Consider the signals shown in Figure 7. If the VCO frequency and the signal A with the lower frequency 980Hz are applied to the inputs of the phase detector XOR, the narrower width of output pulse will cause the low-pass filter obtaining the smaller output voltage of 1V. This smaller voltage decreases the VCO frequency close to the input frequency. If the VCO output frequency equals the input frequency, lock will result. On the contrary, the higher frequency 1.2 KHz of input signal B causes the larger filter output of 3V that increases the VCO frequency output to lock at the input frequency.

PRELAB

Direct FM Using VCO

Perform a PSPICE simulation of a direct FM using a VCO. The VCO is located under anl_misc.olb of the ORCAD library. Change the VCO parameter FCENTER to your carrier frequency and FRANGE to your message frequency. Show your message wave, carrier wave, and the FM signal. Submit your schematics and waveforms.

EXPERIMENT

1-VCO

A suitable set-up for measuring some properties of a VCO is illustrated in Figure 5.
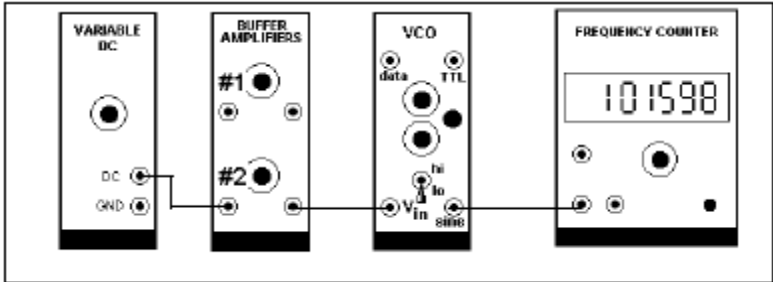
Figure 5: FM generator

For this experiment you will need to measure the sensitivity of the frequency of the VCO to an external control voltage, so that the frequency deviation can be set as desired.

The mean frequency of the VCO is set with the front panel control labeled f_o. f_o vary in two ranges that can be selected using front panel switch indicates "Lo" for low frequencies and "Hi" for high frequencies.

The mean frequency can as well be varied by a DC control voltage connected to the V_{in} socket. Internally this control voltage can be amplified by an amount determined by the setting of the front panel GAIN control. Thus the frequency sensitivity to the external control voltage is determined by the GAIN setting of the VCO.

A convenient way to set the sensitivity (and thus the GAIN control, which is not calibrated), to a definable value, is described below.

T1 *before plugging in the VCO, set the mode of operation to 'VCO' with the on-board switch SW2. Set the front panel switch to 'LO'. Set the front panel GAIN control fully anti-clockwise.*

T2 *connect up the model of Figure 5.*

T3 *use the FREQUENCY COUNTER to monitor the VCO frequency. Use the front panel control f_o to set the frequency to 10 kHz.*

Deviation sensitivity

T4 *set the VARIABLE DC module output to about +2 volt. Connect this DC voltage, via BUFFER #2, to the V in socket of the VCO.*

T5 *with the BUFFER #2 gain control, set the DC at the VCO Vin socket to exactly -1.0 volt. With the VCO GAIN set fully anti-clockwise, this will have no effect on f_o.*

T6 *increase the VCO GAIN control from zero until the frequency changes by 1 kHz. Note that the direction of change will depend upon the polarity of the DC voltage.*

*The GAIN control of the VCO **is now set** to give a 1 kHz peak frequency deviation for a modulating signal at Vin of 1 volt peak.*

The gain control setting will now remain unchanged.

For this setting you have calibrated the sensitivity, S, of the VCO for the purposes of the work to follow.

Here:

$$S = 1000 \text{ Hz/volt} \tag{22}$$

Deviation linearity

The linearity of the modulation characteristic can be measured by continuing the above measurement over a range of input DC voltages. If a curve is plotted of DC volts versus frequency deviation the linear region can be easily identified.

A second, dynamic, method would be to use a demodulator, using an audio frequency message. This will be done later. In the meantime:

T7 *take a range of readings of frequency versus DC voltage at Vin of the VCO, sufficient to reveal the onset of non-linearity of the characteristic. This is best done by producing a plot as the readings are taken.*

T8 *Now replace DC voltage with a single-tone message from " Audio Oscillator" module. Watch VCO output in the oscilloscope. What do you think about FM signal appearance?*

Don't pack up this FM modulator. You will demodulate it in next section using zero-crossing counter demodulation.

2-FM Zero-crossing Demodulator

A simple FM demodulator, if it reproduces the message without distortion, will provide further confirmation that the VCO output is indeed an FM signal.

A scheme for achieving this result was introduced earlier - the zero-crossing-counter demodulator - and is shown modeled in Figure 6.
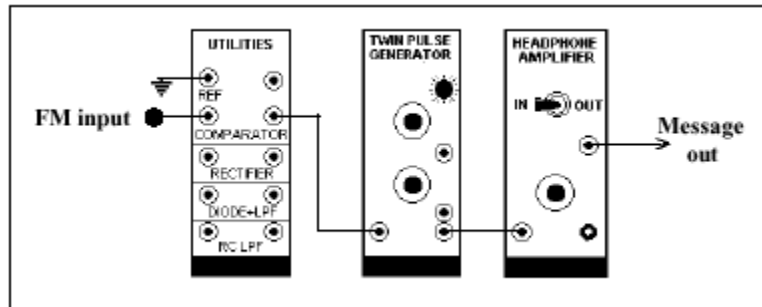
Figure 6: FM demodulator using a zero-crossing demodulator

The TWIN PULSE GENERATOR is required to produce a pulse at each positive going zero crossing of the FM signal. To achieve this, the FM signal is converted to a TTL signal by the COMPARATOR, and this drives the TWIN PULSE GENERATOR.

note: the input signal to the HEADPHONE AMPLIFIER filter is at *TTL* level. It is TIMS practice, in order to avoid overload, not to connect a TTL signal to an analog input. Check for overload. If you prefer, you can use the yellow analog output from the TWIN PULSE GENERATOR. This is an AC coupled version of the TTL signal.

T9 *before plugging in the TWIN PULSE GENERATOR set the on-board* MODE *switch SW1 to* SINGLE*. Patch up the demodulator of Figure 6.*

T10 *set the frequency deviation of the FM generator to zero, and connect the VCO output to the demodulator input.*

T11 *using the WIDTH control of the TWIN PULSE GENERATOR adjust the output pulses to say a mark/space ratio of 1:1.*

T12 *observe the demodulator output. If you have chosen to take the TTL output from the TWIN PULSE GENERATOR there should be a DC voltage present. Why? Notice that it is proportional to the width of the pulses into the LPF of the HEADPHONE AMPLIFIER.*

T13 *introduce some modulation at the VCO with the BUFFER amplifier gain control. Observe the output from the LPF of the HEADPHONE AMPLIFIER using the oscilloscope. Measure its frequency (and compare with the message source at the transmitter).*

T14 *show that the amplitude of the message output from the demodulator:*

a) varies with the message amplitude into the VCO. Is this a linear variation?

b) varies with the pulse width from the TWIN PULSE GENERATOR. Is this a linear variation?

c) is constant with the frequency of the message to the VCO. Does this confirm the VCO is producing FM, and not PM?

T15 *increase the message amplitude into the VCO until distortion is observed at the receiver output. Can you identify the source of this distortion? Record the amplitude of the message at the VCO. You may need to increase the GAIN of the VCO.*

3- FM demodulation with PLL

In this section you will demodulate a FM signal based on a nominal 100 kHz carrier. You will model the PLL, and recover the message from the FM signal. You need two "VCO" modules for this section one to generate FM and second one for construct PLL.

T16 *Set the front* panel switch *of modulator VCO to "Hi". Set the output frequency around 100* kHz *using frequency counter.*

T17 *Set the "Gain" control around the middle and apply a single-tone message from Audio oscillator to the input of VCO. You can use buffer amplifier before it if it needs amplification. Be sure that the "Error" LED in front of VCO in "off". If not adjust the input amplitude to turn it off.*

T18 *make a model of the PLL of Figure 4. Use the Tunable LPF module in "wide" mode. Remember to set up the VCO module in 100 kHz VCO mode. In the first instance set the front panel* GAIN *control to its mid-range position.*

T19 *examine, with your oscilloscope, the FM signal at the output of modulator VCO. Identify those features which suggest it could indeed be an FM signal.*

T20 *connect the FM signal to the PLL.*

The PLL may or may not at once lock on to the incoming FM signal. This will depend upon several factors, including:

- the frequency to which the PLL is tuned

- the capture range of the PLL

- the PLL loop gain - the setting of the front panel GAIN control of the VCO

You will also need to know what method you will use to verify that lock has taken place.

When you have satisfied yourself that you understand the significance of these considerations then you should proceed.

T21 *make any necessary adjustments to the PLL to obtain lock, and record how this was done. Measure the amplitude and frequency of the recovered message (if periodic), or otherwise describe it (speech or music?). Are any of these measurements dependent upon the setting of the VCO GAIN control?*

T22 *measure the properties of each element of the PLL, and then predict some of its properties as a demodulator. If the message was a single tone, from its amplitude can you estimate the frequency deviation of the FM signal?*

T23 *set up input FM signal's frequency deviation to say 5 kHz as described in the section*

T24 *compare the waveform and frequency of the message at the transmitter, and the message from the demodulator.*

T25 *check the relationship between the message amplitude at the transmitter, and the message amplitude from the demodulator.*

T26 *as a further confidence check, use the more demanding two-tone signal as a test message. The two tones can come from an AUDIO OSCILLATOR and the 2.033 kHz message from the MASTER SIGNALS module, combined in an ADDER.*

TUTORIAL QUESTIONS

Q1 *the signal of eqn.(7) appears across a 50 ohm resistor. What power is dissipated in the resistor for the case E = 5 volts and* β *= 5?*

Q2 *calculate the number of sideband pairs required in the signal*

$$y(t) = Ecos(\omega t + \beta cos \mu t)$$

so that it contains 95% of the power in the unmodulated carrier.

Consider the cases: β *= 1, and* β *= 5*

Q3 *in the Tables of Bessel Coefficients you will see some entries are negative. Of what significance is this with relation to the spectrum of an FM signal?*

Q4 *a frequency modulated transmitter radiates a signal at 100 MHz, derived from a 2.5 kHz single tone message. The transmitter output peak frequency deviation is* Df *= 10 kHz. What is the bandwidth of the FM signal on the 1% significant sideband criterion?*

If the message frequency is changed to 10 kHz, what now is the bandwidth on the same criterion?

Q5 *an FM signal with a peak frequency deviation of 20 kHz on a 160 MHz carrier is multiplied with a 100 MHz* sine wave *and the products at 260 MHz selected with a bandpass filter. What is the frequency deviation of the 260 MHz signal?*

Q6 *name some applications where moderate carrier instability of an FM system is acceptable.*

Q7 *what will the FREQUENCY COUNTER indicate when connected to the FM signal from the VCO? Discuss possibilities.*

Q8 *what is a magnitude for* β, *in* $J_n(β)$, *for a Bessel zero, if:*

      a) n = 1   *b) n = 3*

Q9 *define capture range, lock range, demodulation sensitivity of the PLL as an FM demodulator. What other parameters are important?*

Q10 *how does the sensitivity of the VCO, to the external modulating signal, determine the performance of the demodulator?*

Q11 *what is the significance of the bandwidth of the LPF in the phase locked loop?*