Phase locked loop FM detector (PLL FM demodulator)

Phase locked loop, PLL FM detectors can easily be made from the variety of phase locked loop integrated circuits that are available, and as a result, PLL FM demodulators are found in many types of radio equipment ranging from broadcast receivers to high performance communications equipment. The PLL technology started to be used when integrated circuits took over for many radio functions. The PLL could easily be integrated into the radio IC by simply adding a little extra circuitry to the IC. This added very little cost and only required a few external components - normally just resistors and capacitors which are cheap.

The PLL technology eliminates the costly RF transformers needed for circuits like the ratio FM detector and the Foster Seeley circuit. Typically a phase locked loop FM demodulator does not require the use of an inductor, let alone a transformer which is even more costly to manufacture.

PLL FM demodulation basics

The way in which a phase locked loop, PLL FM demodulator works is relatively straightforward. It requires no changes to the basic phase locked loop, itself, utilising the basic operation of the loop to provide the required output.

PLL Phase locked Loop FM demodulator

To look at the operation of the PLL FM demodulator take the condition where no modulation is applied and the carrier is in the centre position of the pass-band the voltage on the tune line to the VCO is set to the mid position. However if the carrier deviates in frequency, the loop will try to keep the loop in lock. For this to happen the VCO frequency must follow the incoming signal, and in turn for this to occur the tune line voltage must vary.

Monitoring the tune line shows that the variations in voltage correspond to the modulation applied to the signal. By amplifying the variations in voltage on the tune line it is possible to generate the demodulated signal. Although no basic changes to the phase locked loop are required for it to be able to demodulate FM, a buffer amplifier is typically provided from the tune line to prevent the tune line being loaded by other sections of the receiver. It provides a lower output impedance and as a result, this prevents loading from the audio amplifier from upsetting the loop in any way.

PLL FM demodulator performance

The PLL FM demodulator is normally considered a relatively high performance form of FM demodulator or detector. Accordingly they are used in many FM receiver applications.

The PLL FM demodulator has a number of key advantages:

Linearity: One of the advantages of the PLL FM demodulator is its high degree of linearity. This is governed by the voltage to frequency characteristic of the VCO within the phase locked loop.Normally the phase locked loop will be able to operate over a wide bandwidth - normally this is much wider than the bandwidth of the FM signal or even the IF stages of the FM receiver. As the frequency deviation of the incoming FM signal covers only a small portion of the PLL bandwidth the overall conversion is very linear.The VCO voltage to frequency curve is the main determining factor and this can be made to be very linear for the range needed for FM demodulation. Distortion levels for PLL FM demodulators are normally very low and are typically of the order of a tenth of a percent. This makes the PLL FM demodulator a very good option for high fidelity tuners as well as for many other applications including radio communications, etc.

Insensitive to amplitude noise: In general the phase locked loop FM demodulator is very insensitive to amplitude noise. As the phase locked loop will track the frequency of the incoming signal, it provides a relatively high degree of AM noise immunity. Obviously it can help if the IF amplifier of the radio is run into saturation such that the signal level is limited and noise is removed, but even on its own the PLL FM demodulator provides good noise immunity.

Ease of incorporation into ICs: Phase locked loops are very easy to implement in an integrated circuit. PLLs have long been available as ICs and this has meant that the technology is easy to implement. Also the PLL FM demodulator blocks are available for IC designers, and therefore many radio IF amplifier ICs have demodulators for AM and FM built in. Often the FM demodulator can be a phase locked loop demodulator.

Manufacturing costs: As the phase locked loop FM demodulator lends itself to integrated circuit technology, only a few external components are required to complete the FM demodulator. One particular advantage is that often no inductor is required for the VCO circuit.

As inductors are relatively expensive components, this can considerably reduce overall component costs and make this approach very attractive for large scale manufacture. These facts make the PLL FM demodulator particularly attractive for modern applications.

PLL FM demodulator design considerations

When designing a phase locked loop system for use as an FM demodulator, one of the key considerations is the loop filter. This must be chosen to be sufficiently wide that it is able to follow the anticipated variations of the frequency modulated signal. Accordingly the loop response time should be short when compared to the anticipated shortest time scale of the variations of the signal being demodulated.

A further design consideration is the linearity of the VCO. This should be designed for the voltage to frequency curve to be as linear as possible over the signal range that will be encountered, i.e. the centre frequency plus and minus the maximum deviation anticipated.

In general the PLL VCO linearity is not a major problem for average systems, but some attention may be required to ensure the linearity is sufficiently good for hi-fi systems. Phase locked loop FM demodulators are used in many radio receivers both domestic and professional for the demodulation of FM signals. The PLL FM demodulator provides a very attractive option in many instances, offering exceedingly low levels of distortion, and the ability to be incorporated into integrated circuit technology.

PLL FM Demodulator

A Phase-Locked Loop (PLL) is basically a negative feedback system. It consists of three major components such as re multiplier, a loop filter and a voltage controlled oscillator (VCO) connected together in the form of a feedback loop. A VCO is a sine wave generator whose frequency is determined by the voltage applied to it from an external source. It means that any frequency modulator can work as a VCO. A phase-locked loop (PLL) is primarily used in tracking the phase and frequency of the carrier component of an incoming FM signal. PLL is also useful for synchronous demodulation of AM-SC (i.e., Amplitude Modulation with Suppressed carrier) signals or signals with few cycles of pilot carrier. Further, PLL is also useful for demodulating FM signals in presence of large noise and low signal power.

This means that, PLL is most suitable for use in space vehicle-to-earth data links or where the loss along the transmission line or path is quite large. Recently, it has found application in commercial FM receivers.

The block diagram of a PLL is shown in Figureure.2.6.1 below.

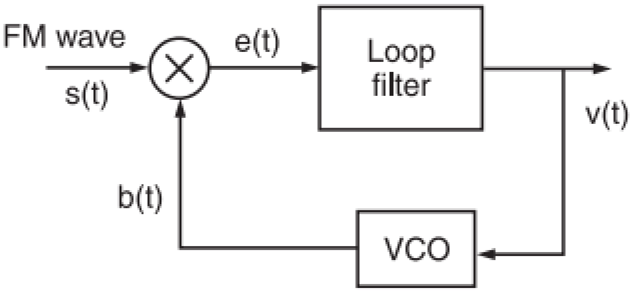

Figure. 2.6.1 The block diagram of a Phase-Locked Loop (PLL)

Diagram Source Brain Kart

Working Operation

The operation of a PLL is similar to any other feedback system where the feedback signal tends to follow the input signal. If the signal fed back is not equal to the input signal, the error signal will change the value of the fed back signal until it is equal to the input signal. The difference signal between s(t) and b(t) is called an error signal.A PLL operates on a similar principle except for the fact that the quantity feedback is not the amplitude, but a generalized phase Φ(t). The error signal or difference signal e(t) is utilized to adjust the VCO frequency in such a way that the instantaneous phase angle comes close to the angle of the incoming signal s(t). At this point, the two signals s(t) and b(t) are synchronized and the PLL is locked to the incoming signal s(t).

Mathematical Explanation

Here, we have assumed that the VCO is adjusted initially so that when the control voltage comes to zero, the following two conditions are satisfied:

(i) The frequency of the VCO is precisely set at the unmodulated carrier frequency fc
(ii) The VCO output has a 90° phase-shift w.r.t. the unmodulated carrier wave.

Let the input signal applied to the PLL be an FM wave. It is defined as ,

$$s(t) = A \sin [\omega_c t + \phi_1(t)] \qquad (1)$$

where A is the unmodulated carrier amplitude and ωc = 2πfc = Angular carrier frequency and

$$\phi_1(t) = 2\pi k_f \int_0^t x(t)\,dt \qquad (2)$$

where x(t) is the message or baseband signal or modulating signal

and kf = frequency sensitivity of frequency modulator. Let the VCO output be defined by,

$$b(t) = A_v \cos[\omega_c t + \phi_2(t)] \qquad (3)$$

there Av = Amplitude of VCO output when the control voltage applied to the VCO is denoted

$$\phi_2(t) = 2\pi k_v \int_0^t v(t)\,dt$$

by v(t), then, we have, kv is the frequency sensitivity of VCO, measured in Hertz/volt.
It may be observed from equations (1) and (3) that the VCO output and the incoming signals are 90° out of phase, while the VCO frequency in absence of v(t) is precisely equal to the unmodulated frequency of the FM signal. The incoming FM have s(t) and the VCO output b(t) are applied to a multiplier. The output of the multiplier has the following components:

(i) A high frequency component represented by,

$$k_m A A_v \sin[2\omega_c t + \phi_1(t) + \phi_2(t)] \qquad (5)$$

(ii) A low frequency component represented by,

$$k_m A\,A_v \sin[\phi_1(t) - \phi_2(t)] \qquad (6)$$

where km = Multiplier Gain measured in per volt.

The high frequency component can be eliminated by using a filter. Hence, discarding the high frequency component, the effective input to the low pass filter (LPF) will be given by,

$$\phi_e(t) = \phi_1(t) - \phi_2(t)$$

This means that

$$\phi_e(t) = \phi_1(t) - 2\pi k_v \int_0^t v(t)\,dt \tag{7}$$

The loop filter operates on error signal e(t) to produce the output v(t). It is given by,

$$v(t) = \int_{-\infty}^{\infty} e(\tau)\,h(t-\tau)\,d\tau$$

where h(t) = Impulse response of the low-pass filter (LPF).

$$\phi_e(t) = \phi_1(t) - 2\pi k_m k_v A\,A_v \int_0^t \int_{-\infty}^{\infty} \sin[\phi_e(\tau)]\,h(t-\tau)\,d\tau dt$$

$$\phi_e(t) = \phi_1(t) - 2\pi k_o \int_0^t \int_{-\infty}^{\infty} \sin[\phi_e(\tau)]\,h(t-\tau)\,d\tau dt$$

Where $k_o = k_m k_v A\, A_v$

Now, differentiating both sides of equation , we get,

$$\frac{d\phi_e(t)}{dt} = \frac{d\phi_1(t)}{dt} - 2\pi k_o \int_{-\infty}^{\infty} \sin[\phi_e(\tau)]\,h(t-\tau)\,d\tau \tag{8}$$

Here, k_o has the dimension of frequency. On the basis of equation we can construct and equivalent model of PLL as shown in Figure. 2.6.2 given below.

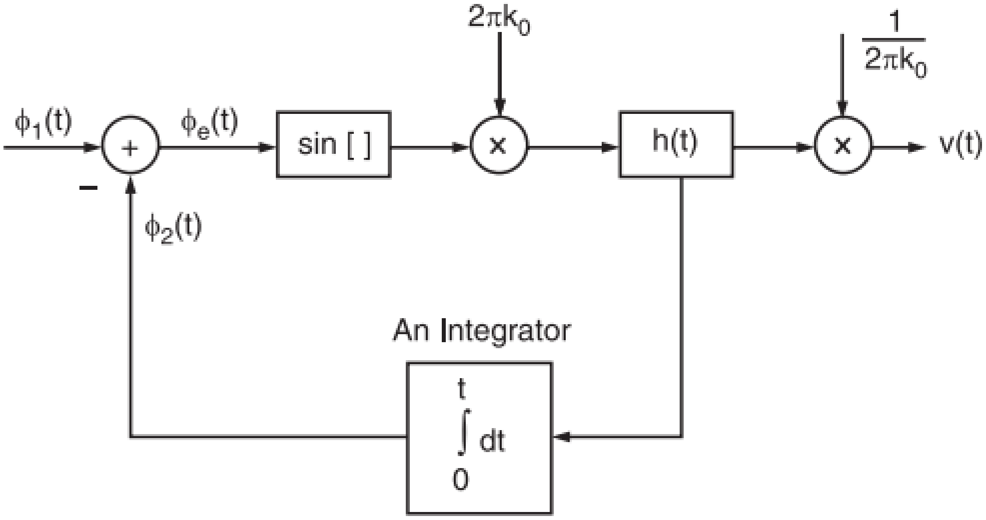

Figure 2.6.2 A non-linear equivalent model of PLL

Diagram Source Brain Kart

In this model, v(t) and e(t) are also included utiliZing the relationship between them as given in equations,

$$e(t) = k_m A\,A_v \sin[\phi_e(t)]$$

and

$$v(t) = \int_{-\infty}^{\infty} e(\tau)]\,h(t-\tau)\,d\tau$$

we can see that they are similar except for the fact that the multiplier in the equivalent model has been replaced by a subtractor and a sinusoidal non-linearity and the VCO by an integrator. When the phase error Φe(t) is zero, then PLL is said to be phase-locked. When the phase error Φe(t) at all times is small compared to 1 radian, then we can approximate sin[Φe(t)] as Φe(t), i.e.,

$$\sin[\phi_e(t)] \cong \phi_e(t) \tag{9}$$

It is almost accurate as long as Φe(t) is less than 0.5 radian. In this case, PLL is said to be Near-Lock Condition and the sinusoidal non-linearity can be discarded.

The linearized model of PLL is valid under above-mentioned condition as shown in Figure 2.6.3.

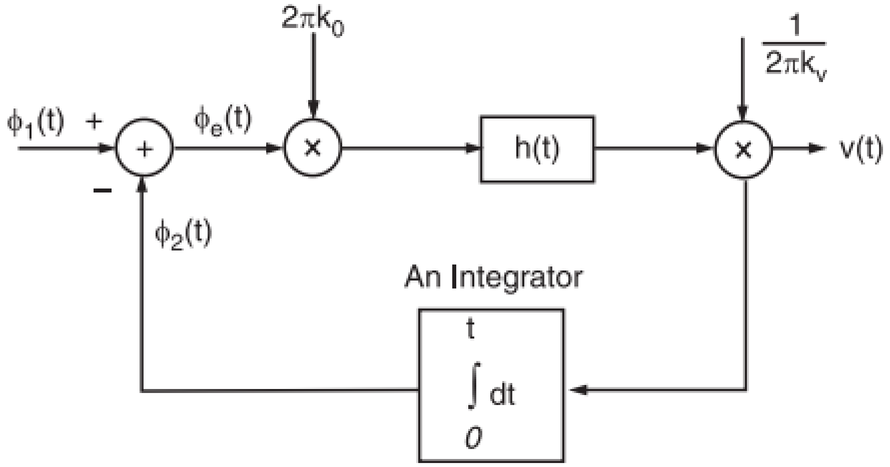

Figure. 2.6.3 Equivalent model of PLL

Diagram Source Brain Kart

In this model, phase error Φe(t) is related to the input phase Φ1(t) by the Integro-differential equation. It is expressed as,

$$\frac{d\phi_e(t)}{dt} + 2\pi k_o \int_{-\infty}^{\infty} \phi_e(\tau)\, h(t-\tau)\, d\tau = \frac{d\phi_1(t)}{dt}$$

Taking the Fourier transform of both sides of equation (10), we get,

$$\Phi_e(f) = \frac{1}{1 + k_o \frac{H(f)}{jf}} \Phi_1(f)$$

where Φe(f) and Φ1(f) are the Fourier transform of Φe(t) and Φ1(t), respectively and H(f) is the Fourier transform of impulse response h(t) and is known as transfer function of the loop filter. The quantity ko(H(f)/ jf is called the open loop transfer function of the PLL.

$$L(f) = \frac{k_o H(f)}{jf}$$

Substituting L(f) in the previous equation , we get,

$$\Phi_e(f) = \frac{1}{1 + L(f)} \Phi_1(f)$$

Now, let us consider that for all values of frequency f inside the baseband signal, we make the magnitude of L(f) very large compared to unity. Thus, from equation (10) we get,

$$\Phi_e(f) \to 0 \text{ as } L(f) >> 1 \qquad (10)$$

Under above-mentioned condition, the phase of the VCO becomes asymptotically equal to the phase of the incoming wave and the phase lock is thereby established.