Voltage-controlled Oscillators (VCO), Phase Locked Loop, and Frequency Converters

Voltage-controlled oscillators are specialized oscillators in which the oscillation frequency varies with a control voltage. VCOs are used in many communication applications such as frequency modulation, in the phase locked loop (PLL) for signal tracking and FM demodulation. There are many ways to design an electronic circuit for a VCO. One method uses a special diode called Varactor. This diode has capacitance that varies with the applied voltage. As the capacitance varies the applied voltage so does the time constant of the oscillator resulting in an output signal with varying frequency. VCO can also be designed by making the time constant of the capacitor dependent upon a control voltage. In this assignment you’ll build a VCO using the analog multiplier used in AM modulator (AD633) and a high frequency op-amp chip (AD9631). You’ll also study the phase locked loop and a commercially available VCO (CD4046).

Figure 1 shows a functional diagram of an RC circuit using the analog multiplier chip AD633. We are interested in finding transfer function of this circuit with respect to the input $V_i$ and output $V_o$. By examining Fig. 1 we can write the expressions for $V_i$ and $V_o$, which are as follows:

\[
V_o = k_d V_c (V_i - V_f) + V_f \tag{1}
\]

\[
V_f = \frac{1}{C_s} V_o = \frac{1}{RC_s + 1} V_o \tag{2}
\]

or

\[
V_o = (RC_s + 1)V_f \tag{3}
\]
Equating Eqs. (1) and (3) yields

\[(RCs + 1)V_f = k_dV_c(V_i - V_f) + V_f\]

or

\[RCsV_f + V_f = k_dV_cV_i - k_dV_cV_f + V_f\]

or

\[RCsV_f + k_dV_cV_f = k_dV_cV_i\]

or

\[\frac{V_f}{V_i} = \frac{k_dV_c}{RCs + k_dV_c}\]

or

\[\frac{V_f}{V_i} = \frac{k_dV_c}{s + \frac{k_dV_c}{RC}}\]

Equation (8) represents the transfer function (with respect to the output \(V_f\)) of a low-pass filter (LPF) that has a pole at

\[-\frac{k_dV_c}{RC}\]

That means the location of the pole and, therefore, the break frequency of the LPF depends on the control voltage \(V_c\). If we incorporate the circuit of Fig. 1 into a relaxation oscillator we can build an oscillator that has output frequency changing with the control voltage \(V_c\). This kind of oscillator is called a voltage-controlled oscillator or VCO. VCOs are commonly used in frequency modulation (FM) and demodulation as well as phase-locked loop (PLL) circuits.

**Assignment 4.1:** Build the VCO that is shown in Figure 2. Use the following values:

Frequency of the control voltage \(f = 1\) KHz, 100 Hz, 1 Hz, 0.1 Hz
Amplitude of the control voltage = 5 V peak
Use sinusoidal as well as square wave signal for the control voltage
\(V_{SS^+} = +15\) V
\(V_{SS^-} = -15\) V
\(R_f = 100\) Ω
\(R_1 = 1\) KΩ
\(R_2 = 100\) Ω
\(C_1 = 0.1\) μF
Record the waveforms of the signal at the designated point in the circuit. Compute frequency calibration (change in the frequency of the output voltage per unit change in $V_c$) of the VCO. Explain your results.

![Figure 2: Functional diagram of a voltage-controlled oscillator.](image)

**Assignment 4.2:** In this experiment you will study the VCO in the CD4046 phase-locked loop chip. Build the circuit shown in Figure 3.

(a) Use $R_1 = 100$ KΩ and $C_1 = 500$ pF. Apply 15 V at the control voltage input (pin 9) and measure the frequency of the output voltage (pin 4). Decrease $V_c$ in 0.5 V steps until $V_c = 1.0$ V and measure the frequency of the output voltage. Plot $V_c$ vs frequency clearly identifying the minimum, maximum, and the center frequency.

(b) Use $R_1 = 100$ KΩ and $V_c = 7.5$ V. Change $C_1$ from 100 pF to 1.0 µF in 20 appropriate steps and measure the frequency of the output voltage. Plot $C_1$ vs the frequency.

(c) Repeat part (b) with $R_1 = 100$ KΩ.

Explain your results.
Phase-Locked Loop (PLL)

Phase-locked loop (PLL) is a feedback system consisting of a voltage-controlled oscillator, a phase comparator, and a loop filter and shown in Figure 5. The phase comparator compares the phase of the reference signal with the phase of the output of voltage control oscillator and generates an error signal, which is proportional to the phase difference between the reference input and the output of the voltage controlled oscillator. The error signal is used as a control voltage to the voltage controlled oscillator. The voltage controlled oscillator changes the frequency of its output based on the error signal. The change in the frequency of the output of the voltage controlled oscillator is in the direction that reduces the difference in the frequency of the reference input and the output of the voltage controlled oscillator. The negative feedback causes the error signal to eventually approach zero, at which point the frequency of the output of the voltage controlled oscillator becomes the same as the frequency of the reference input and the frequency is said to be locked.

In the set of experiments that follows, we will use a phase locked loop for FM demodulation using Texas Instruments’ chip CD 4046B. Figure 6 shows the functional diagram of that chip. We will also use this chip for FM modulation.

Assignment 4.3: build the circuit shown in Fig. 6.
Figure 5: Functional diagram of the phase-locked loop.

Figure 6: Functional diagram of CD4046 chip.