Lecture 24: Oscillators. Clapp Oscillator. VFO Startup

Oscillators are circuits that produce periodic output voltages, such as sinusoids. They accomplish this feat without any "input" signal, other than dc power. Our NorCal 40A has three:

1. VFO (an LC oscillator),
2. BFO (a crystal oscillator),
3. Transmitter oscillator (also a crystal oscillator).

You've likely had some experience with oscillators, perhaps with the astable multivibrator using the 555 IC. This RC oscillator produces a square-wave output voltage that is useful at low frequencies. Generally used in hobby-type circuits.

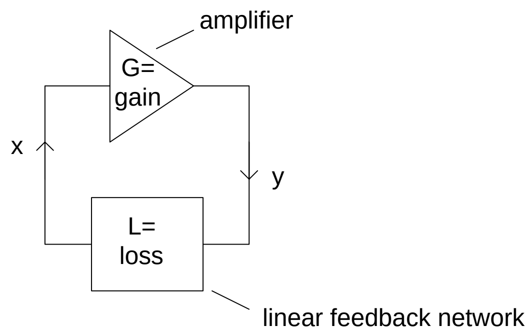
The oscillators in the NorCal 40A are called feedback oscillators. This is a somewhat difficult subject since these oscillators are intrinsically **nonlinear** devices.

Feedback oscillators have three basic parts:

1. An amplifier with signal gain *G*,
2. A linear feedback network with signal loss *L*,
3. A load of resistance *R*.

We'll ignore the effects of *R* for now.

The amplifier and feedback network are connected as shown in Figure 11.1(a):



For the amplifier $$y = Gx \tag{11.1}$$

while for the feedback network $$x = \frac{y}{L} \quad \Rightarrow \quad y = Lx \tag{11.2}$$

Here we have two equations for two unknowns. However, these are not linearly independent equations! If

- $G \neq L \;\Rightarrow\; x = y = 0$. No oscillation is possible.
- $G = L \;\Rightarrow\; y$ and x **may** not be zero. Hence, oscillation is possible.

Generally, G and L are complex numbers, so we have two real equations to satisfy in the equality $G = L$:

1. $|G| = |L|$ – the magnitudes are equal. (11.3)
2. $\angle G = \angle L$ – the phase angles are equal. (11.4)

The meaning of (11.3) is that the gain of the amplifier compensates for the loss of the feedback network. The meaning of (11.4) is that the feedback network compensates for the phase shift (i.e., time delay) of the amplifier.

In a feedback oscillator, **noise** in the circuit will be amplified repeatedly until a single frequency output signal y is produced – a perfect oscillation.

In general, (11.3) and (11.4) can be satisfied for the situations shown in Figs. 11.1(b) and (c). In Fig. 11.1(b), $|G|$ may decreases at high power levels due to amplifier overloading:

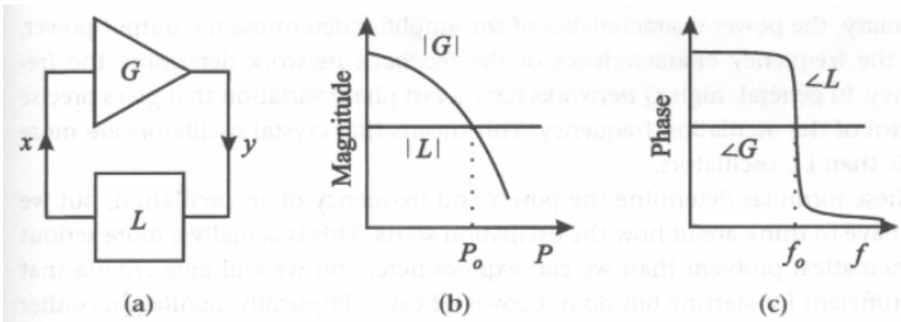


Figure 11.1. Oscillator network consisting of an amplifier with a gain G, and a feedback network with a loss L (a), satisfying the magnitude (b) and phase (c) criteria.

In the NorCal 40A this decreasing $|G|$ occurs because of gain limiting rather than overloading of the amplifier – this scheme yields a cleaner sinusoidal output signal.

The phase criterion in (11.4) is met using a resonant circuit in the feedback network. Why? Because near the resonant frequency of the feedback circuit, the phase $\angle L$ varies rapidly, as shown in Fig. 11.1(c). This characteristic allows precise placement of the oscillator frequency. Clever! (Also has the effect of producing smaller "phase noise.")

Hence, from the two curves in Fig. 11.1 we see that the oscillation criteria are met when

- $|G(P_o)| = |L|$ (at a certain P_o) (11.5)
- $\angle L(f_0) = \angle G$ (at a certain f_0) (11.6)

Oscillator Startup

Another important aspect of oscillators is how they begin oscillating (remember: no input!). The criteria we just derived apply to steady state power at the frequency of oscillation.

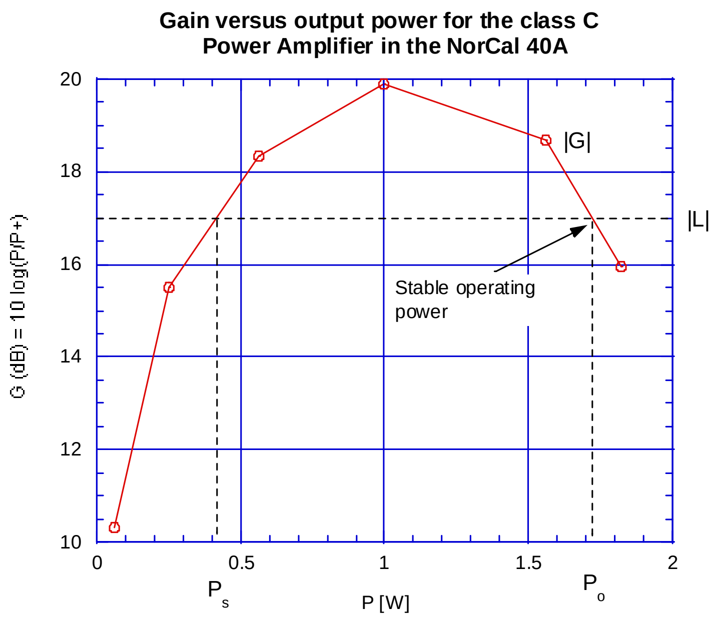
There are two general approaches to starting an oscillator: (1) repeated amplification of noise, or (2) with an external startup signal (as in super-regenerative receivers).

If $|G|>|L|$, then noise that meets the phase criterion (11.6) will be repeatedly amplified. At startup, we will use the small signal gain g to state the start-up criterion for feedback oscillators:

1. $|g|>|L|$, (11.8)
2. $\angle L(f_0)=\angle g$. (11.9)

Interestingly, some oscillators that work well at relatively high power will not start-up by themselves at low power. An example of this is Class C amplifiers, like the Power Amplifier Q7 in the NorCal 40A.

Rather than the gain curve shown in Fig. 11.1(b), class C amplifiers have the gain curve shown below. (This $|G|$ curve was constructed from data collected in Prob. 24.B.)



Class C amplifiers will not oscillate if $P < P_s$. However, once $P > P_s$ oscillation may occur if the feedback network meets the phase criterion (11.9).

It turns out, interestingly, that the oscillators in the NorCal 40A (such as the VFO) actually startup in Class A then shift to Class C as P increases.

Clapp Oscillator

There are many topologies for feedback oscillator circuits. However, all can be divided into two general classes: (1) Colpitts and (2) Hartley oscillators. Each contains an amplifier, a resonator and a voltage divider network to feed some of the output signal back to the input (called "feedback").

In Colpitts oscillators, capacitors form the voltage divider, while inductors form the divider network in Hartley oscillators.

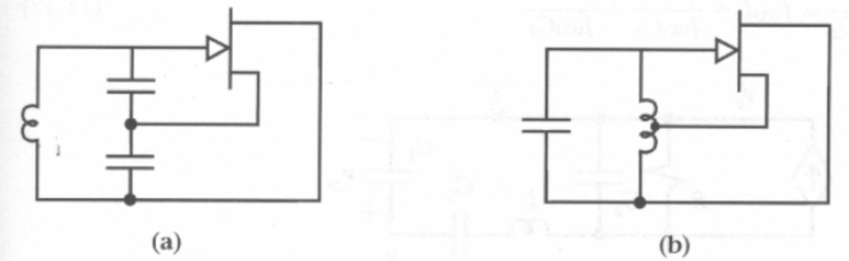


Figure 11.3. Colpitts oscillator, with a capacitive-divider feedback network (a), and Hartley oscillator, with inductor feedback (b). The inductor network is usually made by a connection part way down the coil called a *tap*. The amount of feedback is controlled by the position of the tap. In both figures, the bias and load networks are omitted for simplicity.

The VFO in the NorCal 40A is a Clapp oscillator, which is a member of the Colpitts family since capacitors form the voltage divider network:

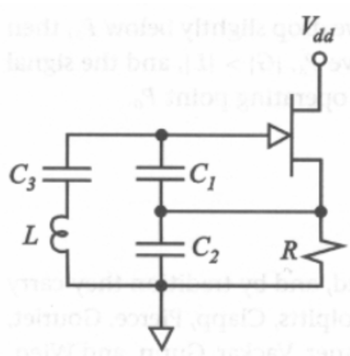
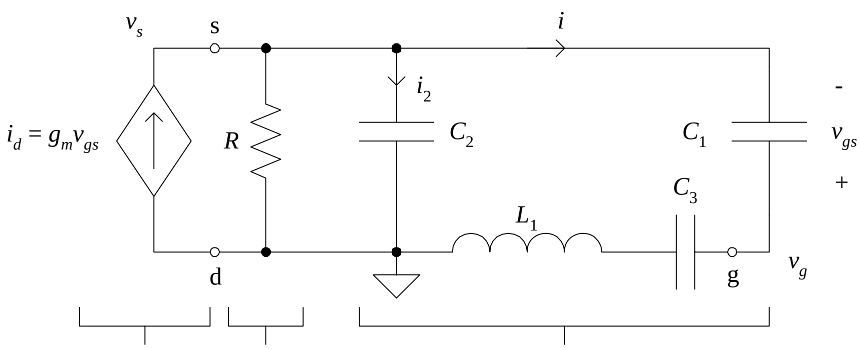


Figure 11.4. Clapp oscillator circuit that is used for the variable-frequency oscillator (VFO) in the NorCal 40A. C_1 and C_2 form the divider network, and R is the load. The gate and source bias networks and the tuning are complicated, and we omit them for now.

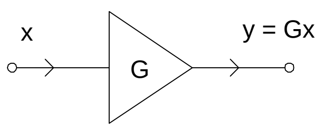
We will analyze the NorCal 40A VFO in two stages. First is startup using small-signal (i.e., linear) analysis. In the next lecture, we will look at steady state using a large signal analysis.

VFO Startup Condition

We can construct the small signal equivalent circuit for the VFO in Fig. 11.4 as shown in Fig. 11.5:



Referring back to Fig. 11.1, the input x in this circuit is v_{gs} while the output y is i_d:



With $i_d = g_m v_{gs}$ for the JFET, we use the small-signal gain $g = g_m$ in the startup criterion (11.8) and (11.9):

1. $|g_m| > |L|$, (11.8)
2. $\angle L(f_0) = \angle g_m$. (11.9)

g_m is a real and positive quantity dependent on the type of JFET and the value of v_{gs}. See Fig. 9.16 (p. 173) for an example (J309).

We'll now solve for v_{gs} in terms of i_d, since L is a ratio of them. This circuit will oscillate at the resonant f of the tank because of the phase criterion (11.9). The resonant frequency f_0 is

$$f_0 = \frac{1}{2\pi\sqrt{L_1 C}} \tag{11.13}$$

where

$$C = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \right)^{-1} \tag{11.14}$$

which is in series with L_1.

Now, at this resonant $f = f_0$, $i + i_2 = 0$ (a key!). Hence, with

$$i_2 = \frac{v_s}{1/(j\omega_0 C_2)} = j\omega_0 C_2 v_s \quad \Rightarrow \quad i = -j\omega_0 C_2 v_s \tag{11.15}$$

Therefore,

$$v_{gs} = -\frac{i}{j\omega_0 C_1} = -\frac{(-j\omega_0 C_2 v_s)}{j\omega_0 C_1} = \frac{C_2}{C_1} v_s \tag{11.16}$$

At resonance, the source terminal of the JFET has the voltage

$$v_s = R i_d \tag{11.17}$$

Substituting (11.17) into (11.16) gives

$$v_{gs} = \frac{C_2}{C_1} R i_d \tag{11.18}$$

This is our needed equation since we have v_{gs} in terms of i_d. Now, by the definition of L in (11.2) and using (11.18):

$$L = \frac{i_d}{v_{gs}} \underbrace{=}_{(11.18)} \frac{C_1}{RC_2} \quad [\text{S}] \tag{11.19}$$

By obtaining this equation, we have solved for the small signal loss factor of the feedback network in Fig. 11.5.

With this L factor now known, it is simple matter to determine the startup condition for the VFO. Specifically, using (11.8) and (11.19), we find that the startup condition for this JFET VFO (Clapp oscillator) is

$$|g_m| > |L| \quad \text{or} \quad g_m > \frac{C_1}{RC_2} \quad [\text{S}] \tag{11.20}$$

In the NorCal 40A, $C_1 = C_2$ (actually C52 = C53) giving the startup condition

$$g_m > \frac{1}{R} \quad [\text{S}] \tag{11.25}$$

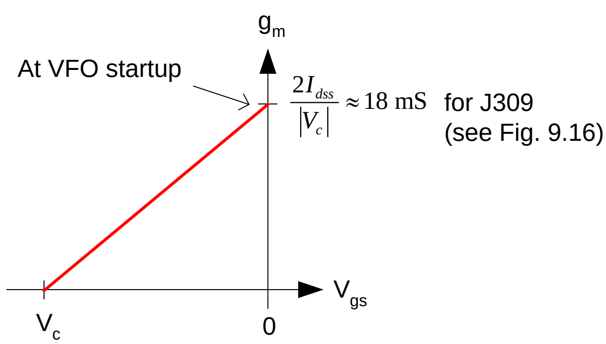
But what about the phase condition $\angle L(f_0) = \angle g_m$? Notice that both g_m and L have zero phase shift at the resonant frequency. Consequently, the phase criterion for startup is intrinsically satisfied.

In summary, if the condition (11.25) is satisfied the VFO circuit in the NorCal 40A will begin to oscillate on its own by repeatedly amplifying noise. Very cool!

Check VFO Startup Design

Let's carefully look at VFO startup in the NorCal 40A. The load resistance R of Fig. 11.5 is R23. The VFO begins oscillation with v_g near zero because of R21, which is why it is called the "start up resistor."

With $v_{gs} \lesssim 0$, then g_m is large:



Now let's check the startup condition. From (11.25), is

$$g_m\Big|_{v_{gs}\approx 0} \overset{?}{>} \frac{1}{\text{R}23}$$

At startup, $g_m \approx 18$ mS while 1/R23 ≈ 0.556 mS. The answer is then yes (by 32x). Therefore, the VFO in the NorCal 40A should easily start up.