HOW TO DESIGN SOLID-STATE OSCILLATORS

An easy-to-follow approach to basic design of this important part of electronic systems.

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THE oscillator is one of the major building blocks of electronic systems. As differentiated from an amplifier, which merely applies gain to any signal fed to its input, the oscillator converts dc applied to its input to an ac signal at its output. Many people who know how to design an amplifier are stymied when it comes to designing oscillators.

There are many types of oscillators. They can be all-electrical or electromechanical. In this article, our concern is with the former, which includes the negative-resistance, Hartley, Colpitts, RC, Armstrong, avalanche, etc., oscillators commonly found in everyday electronic equipment. We will limit our discussion to oscillators that are most practical for the experimenter to use.

Preliminary Information. The configuration of the basic feedback-type oscillator is shown in Fig. 1. It is simply an amplifier to which has been added a feedback network. This type of oscillator goes by various names (Hartley, Colpitts, Armstrong, etc.), but the operation is the same no matter what the name given to it.

If the output of the feedback network is in phase with the input of the amplifier and the output signal of the network is of sufficient level, the amplified output will return to the input and be reamplified. This signal, made even greater in amplitude through double amplification, goes back around to the input of the amplifier continuously, causing the output of the amplifier to alternate in such a manner that the dc power supply voltage to the amplifier is changed to an ac signal at the output of the amplifier. If the feedback network is frequency sensitive, as well as being phase-shifted, the frequency of the oscillator's output signal can be accurately predicted.

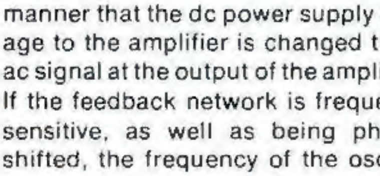


Fig. 1. Basic oscillator is amplifier with feedback.

The obvious problem to the foregoing is that if the feedback energy keeps building each time it is amplified, the ac signal's amplitude will attempt to exceed the dc supply voltage, which is an impossibility. Instead, clipping results and the waveform becomes distorted. In some cases, the distortion is acceptable, but if the oscillator is used in an application such as the vfo (variable-frequency oscillator) in a transmitter, it will cause unacceptable spurious outputs. So, the feedback network must be prevented from feeding too high a signal amplitude to the input of the amplifier. Alternatively, you can reduce amplifier gain. In fact, maximum stability and cleanest waveform occurs when overall gain (including losses in the feedback network) is just slightly greater than unity. If gain is too low, however, there will not be enough feedback to initiate oscillation in the first place and you will end up with an amplifier with frequency-selective positive feedback.

Five basic feedback oscillators are shown in Fig. 2. Each feedback network (tuned circuit) provides the proper phase shift to make the network output in phase with the amplifier's input. In the case of the RC (resistive-capacitive) oscillator, the phase shift in each RC network adds to those of the other networks to produce the total phase shift in the amplifer. Since the proper amount of phase shift occurs at only one frequency, the output frequency of the oscillator is predictable.

The real design problems come in deciding, for example, where to tap the Hartley oscillator's coil, determining the ratios of the capacitors in the Colpitts oscillator, and making sure that the losses in the RC oscillator do not exceed the amplifier's gain so that oscillation can occur.

In the following, we will deal mainly with the Colpitts oscillator, since it is representative of the others and is commonly used in vfo's and other exacting applications where stability must be very good. Another reason for focusing on the Colpitts oscillator is that it is capable of some rather high power levels and it makes a good crystal oscillator simply by replacing the coil with a crystal.

In approaching the design phase, we have three options. First, we can design for maximum stability and little output power. Or, we can forget about stability and go for a lot of power. Finally, we can compromise and design for as much as possible of both stability and output power. Our option will be dictated by the application in which the oscillator is to be used. Whichever option is decided upon, we will use the common-emitter circuit configuration because it yields good power and voltage gain.

Designing the Oscillator. Let us assume we want an oscillator for the vfo in a transmitter. This means that stability must be excellent and the waveform must be clean. Furthermore, the oscillator should be capable of delivering a clean 30-mW signal, which should hardly prove difficult, while maintaining a high degree of stability.

Figure a power supply potential of 9 volts, which can be obtained from an ordinary battery or a zener-diode or IC regulator. Plan on operating the oscillator class A for best stability with an output frequency in the 80-meter (3.5-to-4-MHz) band.

Begin your design by drawing a rough schematic of the oscillator circuit as shown in Fig. 3. Now, determine some of the basic parameters. Start with the load resistance, which is equal to the supply voltage squared divided by two times the output power ($R_L = V_{cc}^2/2P_o$). In your calculations, let V_{cc} be 7 volts to allow some margin of safety. Then, using 7 volts, R_L comes out to 817 ohms, which you can round off to 800 ohms. Pencil in these figures in the appropriate places on your schematic.

The next step is to determine the value of inductance needed. For this, you will have to refresh your memory on Q—the figure of merit for a coil—which is a ratio between the dc resistance of the winding and the winding's reactance at some specific frequency. Most coils have a reasonable enough Q as long as the wire in the winding is not so thin that it inherently exhibits a high dc resistance. Note that our concern here is with the Q that is imposed on the coil by paralleling it with the 800-ohm load. This "loaded Q," or Q_L, is the ratio of the coil's reactance to the load resistance.

If your oscillator used a coil with 800 ohms of reactance and then powered up to 30 mW with an 800-ohm R_L, the ratio would be 800:800 (1:1), which would yield a 3.5-MHz bandwith (output frequency/Q = 3.5 MHz/1 = 3.5 MHz). Remember that bandwidth has a direct bearing on the Q; so, the narrower the bandwidth, the better the Q. (Of course, too high a Q would be detrimental.) A Q of 10 to 20 would be acceptable in our oscillator circuit.

Since the oscillator is to be used as the vfo in a transmitter, where we want the cleanest and most stable signal possible, we will settle for a Q of 20. Now, we must design our coil to have a reactance of 40 ohms.

Choosing a capacitor is a relatively simple task. Rearranging the capacitive-reactance formula $X_C = 1/(2\pi FC)$, we obtain $C = 1/(2\pi FX_C) = 1/(6.28 \times 3.5 \times 10^6 \times 40) = 1.12$ nF. Round this off to 0.001 μF (1000 pF). This would be the total capacitance in the circuit, which means that each of the two capacitors across the coil would have a value of approximately 0.002 μF penciled in on your schematic. Total capacitance $C_T = C1C2/(C1+C2) = 0.002^2/(0.002 + 0.002) = 0.001$ μF.

Feedback Selection. So far, we have done only the easy work. Now we have to start the design of the oscillator itself. First, find a transistor that will give satisfactory performance at 3.5 MHz. A quick look through the manuals reveals that the Motorola HEP-50 transistor has plenty of gain at 3.5 MHz. But let's go a step further to insure that we obtain a stable vfo design.

It is time to identify the components in your schematic, and this time don't forget to draw in tuning capacitor *C5*. You should end up with a circuit like that shown in Fig. 4. Note that single battery biasing would be used for maximum stability.

It would seem that all you have to do is plug in 0.002-μF capacitors for *C1* and *C2* to obtain the required 0.001-μF

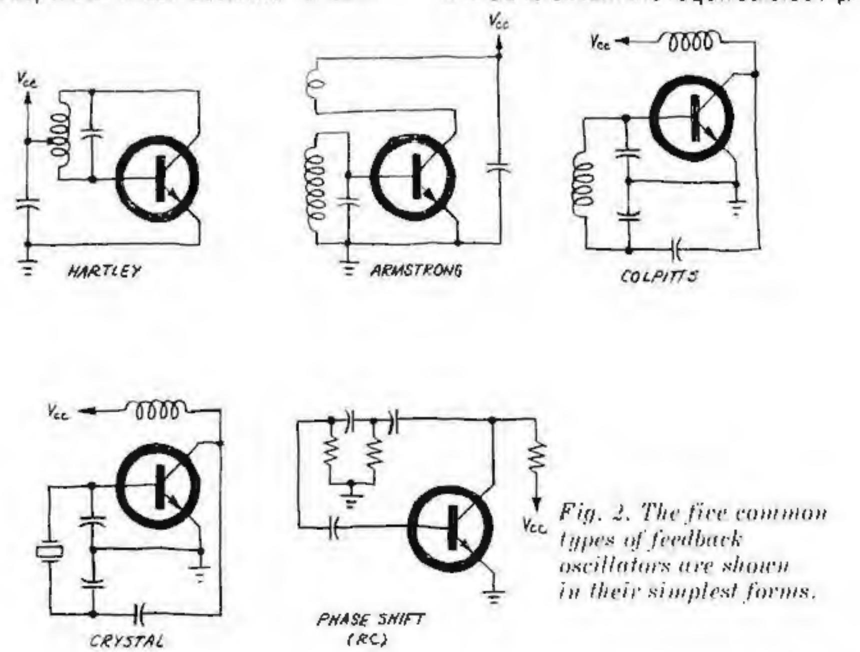


Fig. 2. The five common types of feedback oscillators are shown in their simplest forms.

figure. Make tuning capacitor *C5* small in value—say, a few picofarads—and tweak the slug in coil *L1* a little to lower the inductance to make up for the extra capacitance in the circuit. Then put in the correct biasing resistors.

We mentioned earlier the danger of having the feedback network deliver too much energy to the input of the amplifier. One way to keep the energy down is to add the resistor shown in phantom to reduce stage gain. In many cases, this would be valid. But if you go a step further, your approach will work in all cases.

You can find detailed information on how to design basic amplifier circuits in "Solid-State Circuits for the

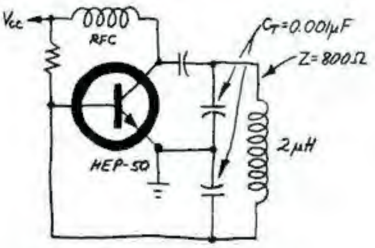


Fig. 3. Start with this basic Colpitts oscillator circuit.

Experimenter" (September 1972 Popular Electronics or 1975 Winter Electronic Experimenter's Handbook). If you can obtain a copy of either, refer to the box to help you fill in the values for the components in Fig. 4.

Use the information given in the box to determine the gain of the amplifier. We know that R_L is 800 ohms. From the information listed on the back of the transistor's box, we know that its β is 85. If you bias the transistor for class A operation, it will be in the middle of its operating range. From Ohm's Law, the maximum current the stage will draw will be: I = E/R = 9 volts/800 ohms = 11 mA. If the stage is in the middle of its operating range, bias it for 5 mA with no signal. From the box, you can see that input impedance Z_{in} is about 400 ohms and stage gain is 160. Divide the gain by 4, which yields a gain of 40. (This is a handy rule of thumb for oscillators.) In designing a Hartley oscillator, you would now select a coil tap that would transform at a 40:1 ratio, and your design would be complete.

We now have a gain of 40. Using the two 0.002-μF capacitors in series would divide the gain by 2 to yield an effective gain of 20. For maximum stability of the oscillator, however, we want the gain to be roughly unity. It would seem logical to allow *C1/C2* equal 20 as in the Hartley oscillator design. However, we want power as well as stability from our oscillator. So, let us pursue another optimum approach to design: impedance matching. This means to obtain maximum power transfer within the oscillator and then adjust the amplifier's gain to obtain a clean output signal. We can assume that matching the impedances is the best approach when power is required from the oscillator.

The capacitive divider provides the impedance match. Impedance ratios in tuned circuits vary as the square of the turns ratio (in this case, the capacitive divider). Now, the object is to find two capacitors whose series capacitance equals about 900 pF, which allows 100 pF for the tuning capacitor *(C5)*. Gain in the amplifier is reduced as necessary by the unbypassed phantomed resistor.

Getting back to the design again, we must sift through a few simple algebra equations. First, the formula for total series capacitance (C_T) is: $C_T = C1C2/(C1 + C2)$. The value of C_T in our example is 900 pF. Next, the ratio of R_{in} to R_{out} is $R_{in}/R_{out} = (n_{in}/n_{out})^2 = [C1/(C1 + C2)]^2$, which translates to the simple formula for determining the value of *C2*: $C2 = C_T\sqrt{R_{out}/R_{in}}$. In our case, C_T = 900 pF, R_{out} = 800 ohms, and R_{in} = 400 ohms. So, $C2 = 900\sqrt{800/400}$ = 1270 pF. The value of *C1* can be determined from the formula: $C1 = C_T/[1 - (C_T/C2)]$ = 3100 pF. Rounding out the two values, we obtain: *C1* = 1200 pF (0.0012 μF) and *C2* = 0.003 μF.

With the oscillator set for maximum power gain, you must now add some negative feedback to obtain the cleanest output signal. The phantomed resistor's value is easy to determine. When it comes time to assemble the circuit, temporarily connect a 500-ohm potentiometer between the transistor's emitter and ground. Adjust the pot, while observing the oscillator's output on an oscilloscope, for the cleanest possible waveform. Then, without touching the setting, remove the pot from the circuit and measure its resistance. Use a fixed resistor of the same or approximately the same value as that measured across the pot in the circuit.

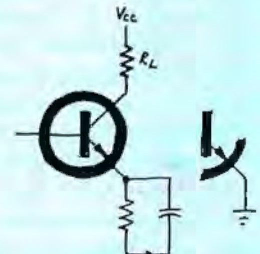
From this point on, it is just finishing touches. The reactance of C3 should be roughly $R_L/10$ = 800/10 = 80 ohms. Using the formula $C = 1/(2\pi FX_C)$, we obtain a figure of roughly 570 pF, which can be rounded out to a more common 0.001-μF value. The reactance of *C4* should be at least $R_{in}/5\beta$ or about 1 ohm in this case. (This value can be adjusted to prevent quenching.) The formula used for *C3*, when applied to *C4*, yields a value of about 0.05 μF. To prevent the r-f choke's (*RFC1*'s) dc resistance from limiting the output of the oscillator, it should be considerably less than the 800-ohm value of R_L. A 2.5-mH choke would look like 55,000 ohms at 3.5 MHz, which should be very effective in comparison to the 800 ohms for R_L.

All that is left now is to assemble the circuit, using the calculated component values, and measure the parameters to determine if all is well with the design.

Design Checkout. The next step is to breadboard your design, preferably with perforated phenolic board and

QUICK AMPLIFIER STAGE DESIGN

Shown below are some rules-of-thumb formulas you can use to design your own common-emitter amplifier stages. Combining this information with the design details given in the text, you can design a complete oscillator stage.



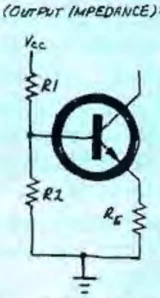
V_G (VOLTAGE GAIN) ≈ $\beta(R_L/Z_{in})$

Z_{in} (INPUT IMPEDANCE) ≈ $\beta(26/I_E^*)$

*I_E IS IN mA

I_G (CURRENT GAIN) ≈ 0.9β

Z_{out} (OUTPUT IMPEDANCE) ≈ R_L



I_C (COLLECTOR CURRENT) ≈ I_E

I_E (EMITTER CURRENT) ≈ V_E/R_E

V_E (EMITTER VOLTAGE) ≈ $V_{CC}[R2/(R1+R2)]$

$R1 = [(R2V_{CC})/V_E] - R2$

$R2 = 5R_E$

V_E = VOLTAGE DROP ACROSS R_E

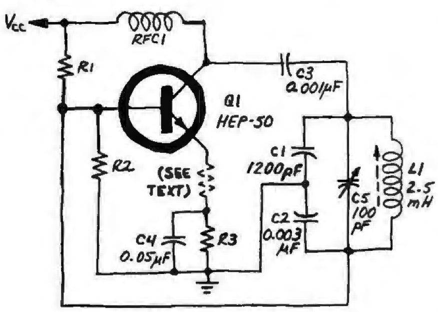


Fig. 4. Here we have added some values and a tuning capacitor.

solderless clips. This will permit you to adjust component values as needed before proceeding to final assembly. Test equipment that will be handy to have during checkout includes a variable power supply, a frequency counter for checking that the oscillator is on-frequency, an oscilloscope to view the output waveform, and a good general-coverage communication receiver to listen for signal purity and check for harmonics.

None of the above test equipment is essential. For example, you could use an ordinary 9-volt battery in lieu of a variable power supply. However, you will need at least a VOM (set to ac volts) or, better yet, an oscilloscope to check for the presence of oscillation.

You can check for instability, in the form of drift, by beating the oscillator's output signal against a known reference signal of good stability, such as from a crystal oscillator. Some of the sources of drift and instability are the input and output capacitances of the transistor itself, which can vary with bias, temperature, supply voltage, etc. There are also coil dimension changes that occur with changes in temperature and instabilities caused by capacitance changes with heating and cooling. All of these can be minimized or limited in some or all of the following ways.

Since transistor parameters vary with changes in bias, single-battery (or regulated-dc) bias systems should be used when stability is a critical factor. To keep the transistor's parameters from changing with variations in the supply voltage, regulate the V_{cc} line with a zener diode or IC regulator. Also, to keep capacitance changes in the transistor junctions at a minimum, use a high-Q, high-LC-ratio tuned circuit. (The major advantage of the Colpitts design is that *C1* and *C2*, whose values we took so much pains to calculate, tend to swamp out the variations in input and output capacitances.) The high LC ratios demand a coil of fewer number of turns, and the wire should be firmly wound on the coil form and held in place with coil dope to minimize dimension changes due to temperature changes.

High-quality capacitors, such as the silver-mica variety, will not be as susceptible to thermal drift as are other types of capacitors. The oscillator should be well ventilated, component leads should be kept short, and all components should be firmly mounted in place to minimize vibrational effects.

Final Touches. Under final touches, we rid our oscillator of spurious oscillations that are common in transistor designs. We will cover only a few of the problems likely to be encountered and their solutions. Most of the problems can be avoided at the time the circuit is still on paper.

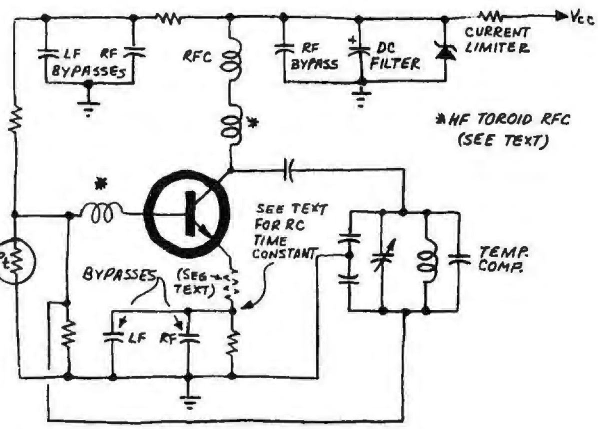
One problem is "quenching" or "squegging." This is a lower-frequency oscillation often caused by too high a time constant in the emitter circuit bypass. It allows the emitter bypass capacitor to charge up to a voltage that eventually cuts off the transistor. This occurs repeatedly at some lower frequency and superimposes itself on the oscillator's output signal. The output signal is then loaded with spurious outputs that may occur every few kilohertz on the radio dial. When quenching occurs, reduce the time constant by making the values of *R3* and *C4* as low as possible and readjusting the bias circuits to compensate for the lower resistance.

Another problem is that of an additional high-frequency oscillation in the circuit. There can also be low-frequency oscillations caused by such things as the inductance of the r-f chokes. The lower frequencies can be minimized by bypassing both r-f and audio frequencies. Higher-frequency parasitics can be minimized by adding r-f chokes that act as high impedances at the parasitic and short circuits at the operating frequency. One such choke can be fabricated by slipping ferrite beads over component leads. You can make your own by winding a turn or two of enameled wire on a toroid core made from a tuning slug of a tunable coil. The hole runs lengthwise along the slug so that a few turns of No. 28 enameled wire wound through the hole makes an excellent parasitic choke.

The schematic diagram shown in Fig. 5 illustrates all design techniques that can be employed in an oscillator. It is doubtful, however, that all of these techniques will be needed in any given oscillator.

Once you've debugged your oscillator design, you can proceed to final assembly. The preferable medium would be printed-circuit board construction, but perforated board and solder clips will serve equally well.

Fig. 5. A completed oscillator circuit which may contain more refinements than you need.



In Conclusion. We've covered one basic type of oscillator here. Obviously, there are many more. The oscillator and approaches used in its design in these pages are very simple and extremely dependable. Using the guidelines, you can design your own oscillator circuits. Special requirements, such as working at temperature extremes, super-high stability, etc., can all be achieved by starting with our modest approach.

You can design crystal oscillators that operate in the series mode by replacing the coil with a crystal in the Colpitts design. You can use pre-tapped coils in Hartley circuits and still design system gain for optimum oscillator performance by adding negative feedback. We can go on and on *ad infinitum*, but you get the idea. ◈