Jim Fisk W1DTY
RFD 1, Box 138
Rindge, New Hampshire 03461

Designing Transistor Oscillators

If you have been having trouble with transistor oscillators, this article will show you how to design them to meet your requirements. Five brand new nomographs eliminate most of the math.

Of all the electronic circuits that the ham must analyze, design, construct and use, oscillators are apt to give him the most trouble. Although oscillators are basic requirements for any radio communications, they are probably cussed at more and understood less than any other singular circuit. Actually, vacuum tube (and FET) oscillators are relatively easy to get going, and except for some thermal drift problems, are fairly simple to tame down. In vacuum tube circuits, you can hang *just* about any tuned circuit across the output, feed a little of the output energy back to the grid, and the thing will take off. It really doesn't *seem* to matter a great deal what the tuned circuit values are so long as they are resonant at the desired frequency. It's this last statement that gets most oscillator builders into trouble. Even though in many cases it doesn't *seem* to matter what the tuned-circuit values are, in almost every instance it *does*, and frequency stability, amplitude stability, and power output can be improved by pursuing proper design.

With the transistor oscillator, it's a little different story; this is because the low value of input impedance associated with a transistor may seriously load the oscillator circuit if it is not properly designed. In fact, if the tuned circuit is not properly designed, chances are the circuit won't oscillate at all. It is the purpose of this article to describe some of the more common transistor oscilla-

tor circuits and to present a simplified method for their design.

Although all oscillator circuits consist of an active device such as a transistor, and some passive elements like capacitors and coils to store energy, there are actually two basic categories of oscillators, *harmonic* and *relaxation*.

In the harmonic oscillator, energy always flows in one direction from the transistor to the tuned circuit, and the frequency of oscillation is determined by the frequency characteristics of the feedback path. In the relaxation oscillator the transistor acts like a large-signal switch which periodically turns on and cuts off the flow of dc power to the passive storage elements in the circuit; its frequency is determined by the charge and discharge time during the exchange of energy. This type of oscillator is normally characterized by a nonsinusoidal output, while the harmonic oscillator primarily produces a sine wave and is of major importance in all radio equipment. Only the harmonic oscillator will be discussed in this article.

Depending upon what frequency selection components are used in the circuit, the output waveform may or may not show in what way it was generated. One important characteristic of the harmonic oscillator is that the transistor is continually applying power to the tuned circuit; in the relaxation oscillator there is an interchange of energy in a discontinuous manner.
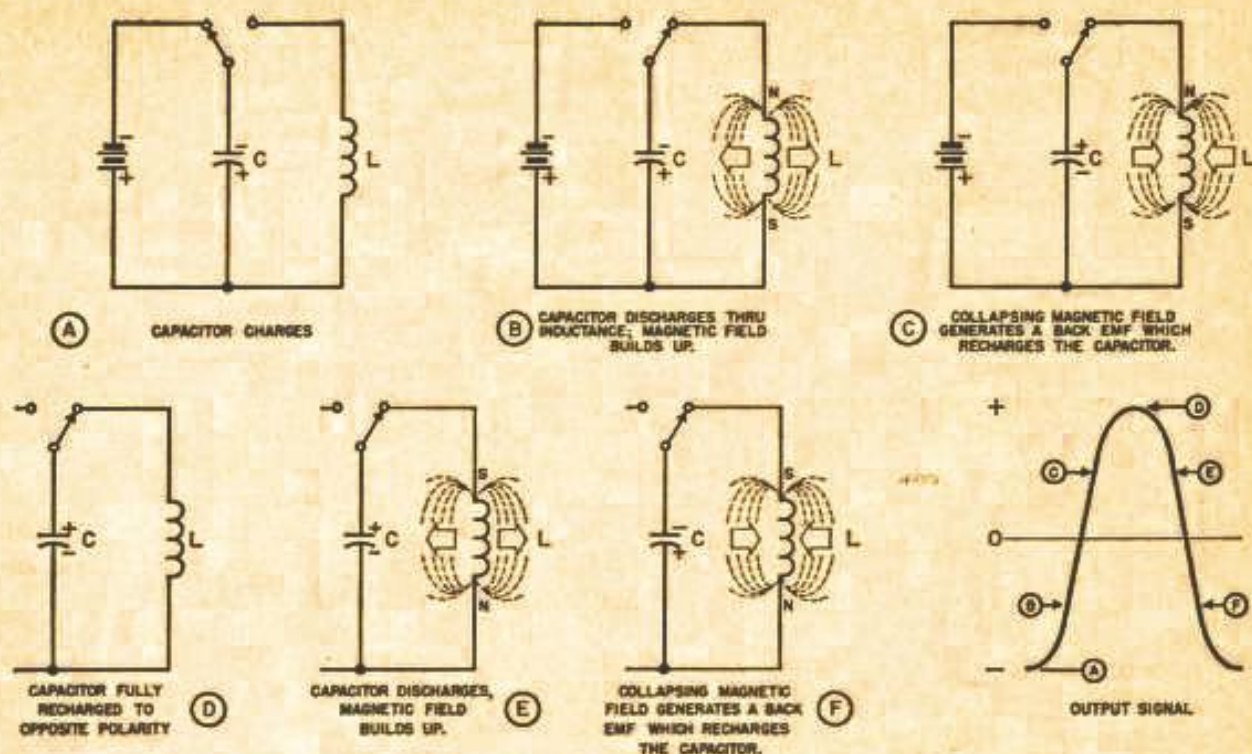
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Fig. 1. Oscillatory action in a simple resonant LC circuit.

Basic oscillator circuit

Before we discuss transistor harmonic oscillators in detail, let's talk a little about the most simple oscillatory circuit of all, the straight-forward L-C circuit illustrated in **Fig. 1.** If the capacitor in the tank circuit is initially charged with a battery (**Fig. 1A**), and then switched in parallel with an inductor (**Fig. 1B**), it will discharge through the inductor. The capacitor doesn't discharge in a single blue flash, but discharges quite slowly because the inductor tends to oppose any change in current through it. As the capacitor starts to discharge, the current in the inductor slowly increases and a magnetic field builds up around the coil. When the capacitor is fully discharged, the magnetic field surrounding the inductor starts to collapse and as it collapses, it generates a current equal in magnitude to the original discharge current, but of opposite polarity (**Fig. 1C**); when the field around the coil is completely collapsed, the capacitor is recharged to the opposite polarity (**Fig. 1D**). However, as soon as the capacitor is recharged, it again seeks equilibrium and discharges through the inductor (**Fig. 1E**); the magnetic field builds up, and when the capacitor is completely discharged, the field collapses, recharging the capacitor to its original polarity (**Fig. 1G**).

This action happens over and over again, with the capacitor and inductor exchanging electrical energy. If there were no losses, this circuit would continue to oscillate back and forth as long as the coil and capacitor were connected in parallel. However, in practical circuits, the coil exhibits a certain amount of resistance and the capacitor doesn't quite regain a complete recharge on each succeeding cycle. The result is that the oscil-
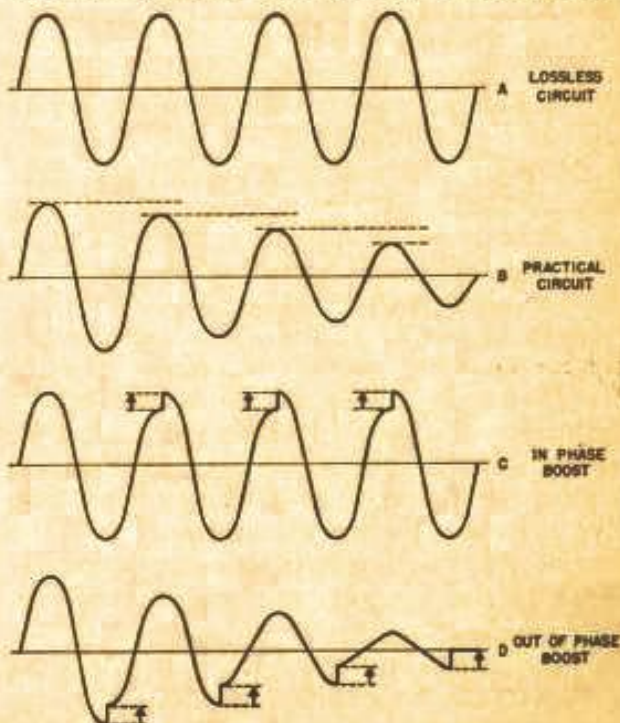

Fig. 2. Idealized waveforms for various operating conditions in harmonic oscillators.
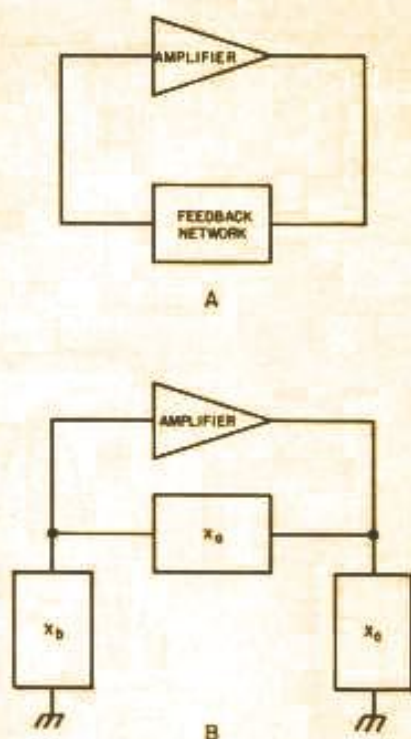
A

B

Fig. 3. All harmonic oscillators consist of an amplifier and a frequency-selective feedback network as shown in A. In the popular Colpitts and Hartley circuits, the feedback network consists of three reactances, X_a, X_b, and X_c as shown in B.

lations slowly decline in magnitude as illustrated in Fig. 2B. To maintain oscillations, a small amount of energy must be added to the circuit once each cycle as illustrated in Fig. 2C. It is here that the transistor or vacuum tube must be used, to provide the little kick of energy once each cycle.

This little kick of energy is a lot more complex than it would appear at first glance. First of all, it must be just large enough to overcome the inherent losses of the circuit; and second, it must occur at just the right time. If the boost does not occur at precisely the right time, it will either do nothing at all, or it will result in the rapid demise of oscillations as shown in Fig. 2D.

Actually, any oscillator may be represented by an amplifier and a frequency selective feedback path similar to that of Fig. 3A; by looking at this block diagram for a moment, we can see exactly what the requirements are for oscillation. First of all, we know that the amount of energy contributed by the amplifier to the tuned circuit must be exactly equal to the energy lost through circuit resistance. In other words, we want an output that is exactly equal to the input; the total gain through the amplifier and frequency selective feedback network must be equal to one or unity.

The other requirement for oscillation is that the kick must occur at just the right time. This is not really so difficult to do once we sit down and think about it—all we are saying is that the kick furnished by the amplifier must be in phase with the oscillator ouput. Since there is a 180° phase shift through the transistor from base to collector, the tuned feedback circuit must provide another 180° phase shift so that the output signal appears in phase with the input. In summary then, to function as an oscillator, the amplifier and frequency selective network must exhibit a total gain of unity and a phase shift of zero (or 360) degrees.

In the two most popular oscillator crcuits, the Colpitts and Hartley, the frequency selective feedback path consists of three reactances denoted as Xa, Xb and Xc in Fig. 3B. In the Colpitts oscillator, Xa is an inductor and Xb and Xc are capacitors. In the Hartley circuit, Xa is a capacitor and Xb and Xc are inductors.

Colpitts oscillator

In the transistor version of the popular Colpitts oscillator in Fig. 4 and 5, capacitors C_1 and C_2 form a resonant tank circuit with the inductance L. A small fraction of the current flowing in the tank circuit is fed back to the base of the transistor through C_2. Although the oscillation frequency is determined primarily by the tank components C_1, C_2, and L, the transistor input impedance (h_{ib}) and output impedance (h_{ob}) affect it
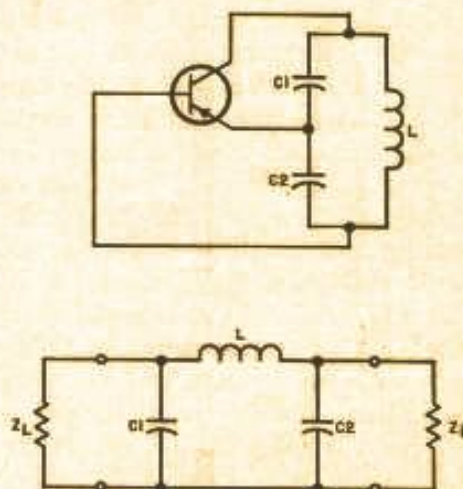

Fig. 4. The basic Colpitts oscillator. Bias resistors and power supplies have been left out for clarity. Since the input and output impedances of the transistor (Z_i and Z_L respectively) load the tuned circuit, the circuit may be further simplified by replacing the transistor with two resistors representing the loading.
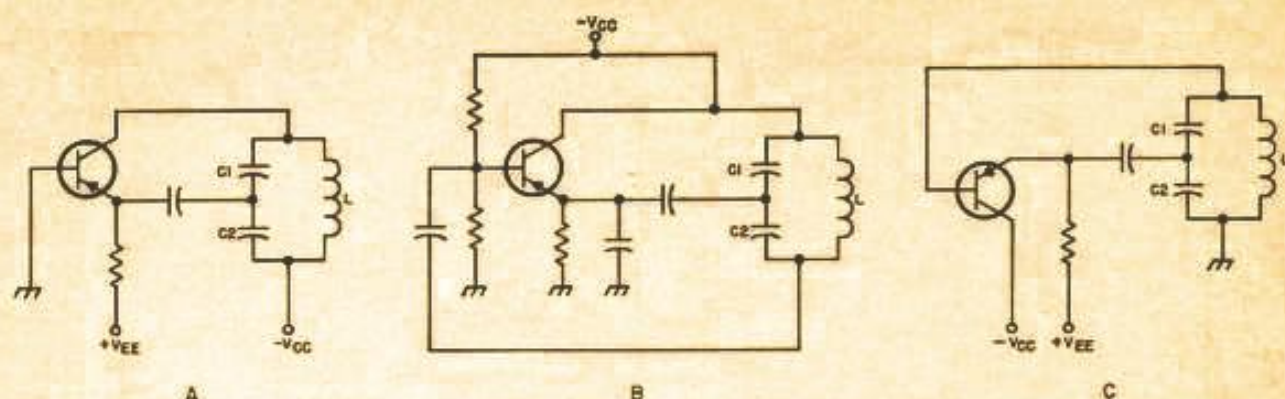
Fig. 5. Practical transistor Colpitts oscillators. The common-base connection is shown in A, the common-emitter in B and the common-collector in C. C3 is the unmarked capacitor connected to the junction of C1 and C2.

slightly. The frequency of oscillation is given by

$$f = \frac{1}{2\pi} \sqrt{\frac{1}{LC_T} + \frac{h_{ob}}{h_{ib}C_1C_2}}$$

where C_T is the equivalent capacitance of C_1 and C_2 in series:

$$C_T = \frac{C_1C_2}{C_1 + C_2}$$

Fortunately, the term $(h_{ob}/h_{ib}C_1C_2)$ is usually quite small, and the frequency of oscillation may be simplified to

$$f = \frac{1}{2\pi \sqrt{LC_T}} = \frac{0.157}{\sqrt{LC_T}}$$

This formula is not difficult to work if you're familiar with the slide rule, but its solution can be quite tedious if done by hand. The nomograph of Fig. 6 does all this work for you. In fact, Fig. 6 may be used in any case where the resonant frequency of a tuned LC circuit must be determined.

For more accurate results, the more complex equation including the term $(h_{ob}/h_{ib}C_1 C_2)$ must be used. In solving this formula, the nomograph will not work. However, usually a slug-tuned coil is used in a practical circuit, so the oscillator may be adjusted to the correct frequency after the oscillator is constructed.

Although predicting the frequency of oscillation is important, it has been previously noted that just any combination of inductance and capacitance that is resonant at the desired frequency will not necessarily cause the circuit to act like an oscillator. From the diagram of Fig. 4 it can be seen that the portion of energy circulating in the tank circuit which is fed back depends upon the size of C_1 and C_2. To ensure that the oscil-

lator will start and sustain oscillations when voltage is applied to the circuit, the common-emitter current gain (h_{fe}) must be greater than the ratio of C_2 to C_1.

$$h_{fe} > \frac{C_2}{C_1}$$

where h_{fe} is the value of forward current gain at the frequency of interest.

Frequency stability

In addition to these two requirements, there is one other important consideration when designing an oscillator—that of frequency stability. Frequency stability is extremely complex because it varies with changes in temperature, power supplies, external circuit components and circuit Q. In addition, frequency drift is a function of amplification, and through amplification, of the collector voltage and emitter or base current. It is also a function of the effective impedance of the tuned circuit, and that impedance is a function of the coupled loads reflected from the input and output loads of the transistor—complex, to say the least. If frequency stability is of paramount importance, the first thing to do is to insure that only a small amount of power is taken from the tank circuit. In most cases a good buffer amplifier will effectively isolate the oscillator from loading and load variations and eliminate many problems with drift.

Theoretically, the frequency stability of an oscillator is independent of the configuration in which the transistor is used. However, degradation of circuit Q by transistor loading and amplification variations must be identical; in practice this is difficult to achieve. This being the case, the best stability can be expected for the circuit arrangement which provides the smallest load-
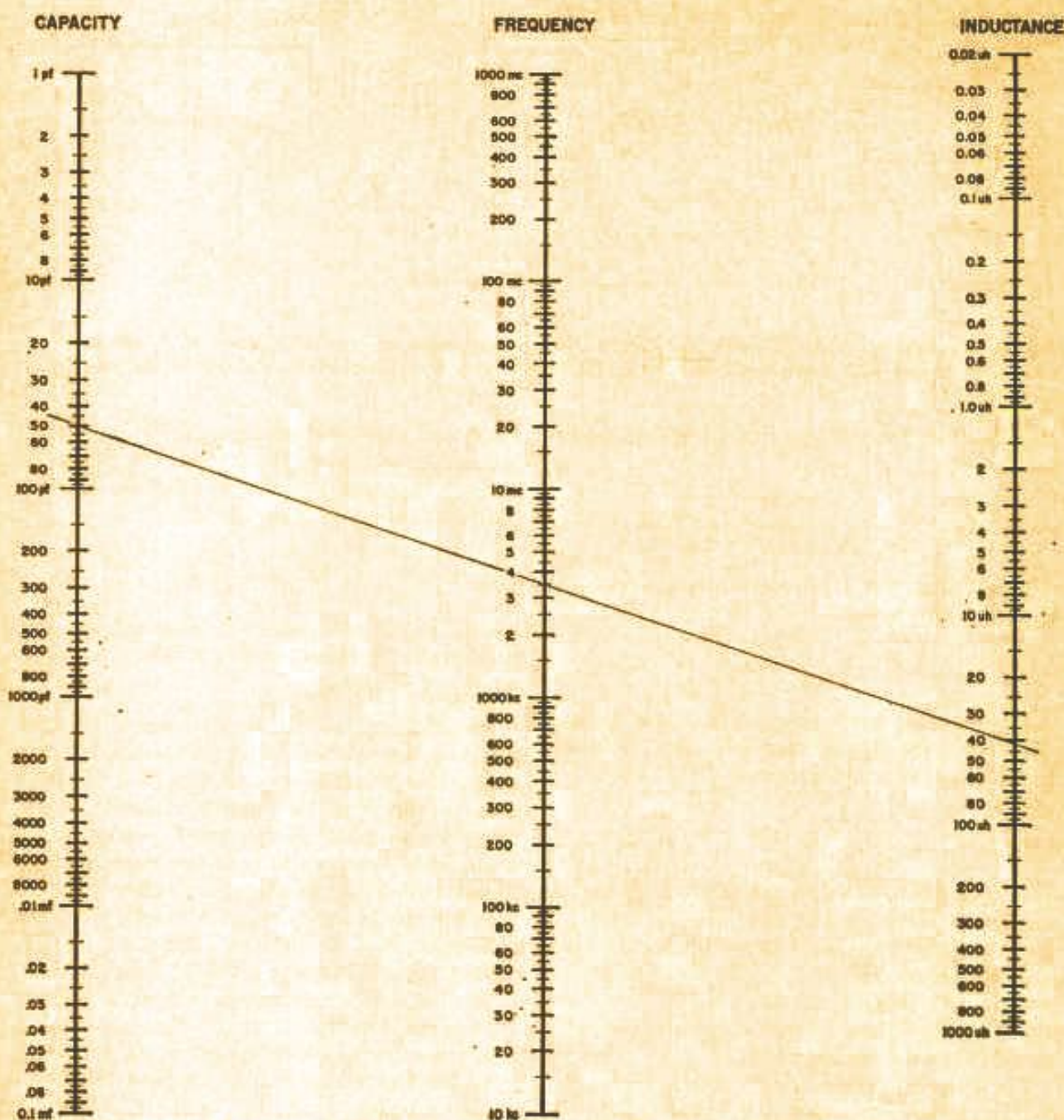
CAPACITY

```
1 pf
2
3
4
5
6
8
10pf
20
30
40
50
60
80
100pf
200
300
400
500
600
800
1000pf
2000
3000
4000
5000
6000
8000
.01mf
.02
.03
.04
.05
.06
.08
0.1mf
```

FREQUENCY

```
1000 mc
900
600
500
400
300
200
100 mc
80
60
50
40
30
20
10 mc
8
6
5
4
3
2
1000 kc
800
600
500
400
300
200
100 kc
80
60
50
40
30
20
10 kc
```

INDUCTANCE

```
0.02 uh
0.03
0.04
0.05
0.06
0.08
0.1 uh
0.2
0.3
0.4
0.5
0.6
0.8
1.0 uh
2
3
4
5
6
8
10 uh
20
30
40
50
60
80
100 uh
200
300
400
500
600
800
1000 uh
```

Fig. 6. Nomograph for determining the resonant frequency of tuned circuits. It may also be used to find the value of capacitance which will resonate at a given frequency with a given coil, or vise versa. A ruler is laid across the two known quantities and the third may be easily found. In the case illustrated, 42 μH resonates at 3.5 MHz with a 50 pF capacitor.

ing and the smallest variation in gain. The common-base circuit has reduced stability because of the large input signal power required by the emitter and because of the transistor's reduced power gain when conpared to the common-emitter configuration.

The selection of a configuration between the common-emitter (CE) form and the common-collector (CC) or emitter-follower configuration is much more difficult. The power gain of a CC amplifier is much smaller than the CE, but the uniformity of both in load-

ing and gain are much better; consequently, selection between the two can be rather difficult. If the common-emitter circuit is properly designed, it can provide an excellent high stability oscillator; otherwise, the emitter-follower circuit often gives the most stable arrangement. This is borne out by the large number of Clapp and Q-multiplier type emitter-follower oscillators. The improved drift characteristics in both cases is a result of the reduced and uniform loading of the transistor on the tuned circuit and more uni-

form gain.

Temperature variations which result in frequency drift may be largely neutralized by proper biasing techniques or by using temperature sensitive capacitors in the tank circuit. Although the design of bias networks is beyond scope of this article, there have been several excellent articles and books written on the subject.[1,2] Essentially, the bias resistors must be chosen so that the operating point remains relatively fixed with changes in the outside environment. This may often be done economically by using temperature-sensitive resistors; the temperature dependence necessary to stabilize the frequency may be determined quite easily.

A variable resistance is simply inserted into the circuit in place of the temperature-sensitive element. Then the circuit is exposed to the projected temperature range and this resistance is varied to keep the frequency constant. The temperature dependence of the temperature-sensitive resistor is then selected to match the measured temperature curve. This resistance may not necessarily keep the bias point constant, but it will change in such a way that it maintains a constant frequency of oscillation, compensating for more than one fluctuation in the circuit as a function of temperature.

A temperature sensitive capacitor in the tank circuit may be selected by the same technique — a variable capacitor is placed across the tank and adjusted for constant frequency output at the temperature extremes. The compensating capacitor should be chosen to follow the same curve.

Although temperature considerations and circuit loading are both very important to frequency stability, low drift is primarily dependent upon the Q of the tank circuit. All other things being equal, the higher Q circuit always results in lower drift. When the effects of temperature and circuit loading are neglected, the percent of drift is a direct function of Q as shown in Fig. 7. With proper temperature compensation and very light loading, the frequency stability obtained in a practical circuit will very closely approach this curve.

In addition, the tank L/C ratio should be low; this results in a larger value of capacitance in the tank circuit to filter out harmonics which tend toward frequency instability. Also, the self-resonant frequency of the inductors and capacitors in the tank circuit should be at least ten times the operat-
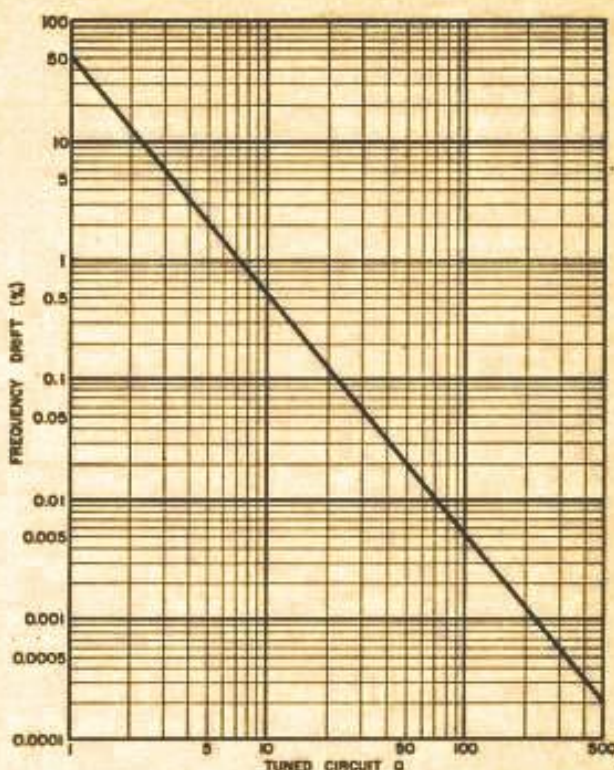

Fig. 7. The affect of tuned-circuit Q on frequency drift in an oscillator. For maximum frequency stability in a practical circuit, the Q should be as high as possible.

ing frequency of the oscillator, and where possible, even larger. Otherwise, the internal parasitic parameters of these tank components will seriously degrade oscillator performance to the point that stability will be unsatisfactory.

Colpitts oscillator design

Since frequency stability is usually the first consideration, circuit Q is a good place to start the design of a transistor oscillator. From the graph of Fig. 7, you can choose a value of Q that is compatible with practical components and will provide the frequency stability required. With this value of Q in mind, the frequency of operation and the desired impedance of the tuned circuit at resonance, the correct value of tank capacitance may be found from

$$C = \frac{Q}{2\pi f Z}$$

Again, the math in this formula, although not completely formidable, is inconvenient, so the nomograph of Fig. 8 was prepared to give you an almost instant answer; the nomograph has the added advantage that you can quickly check the effect of various values
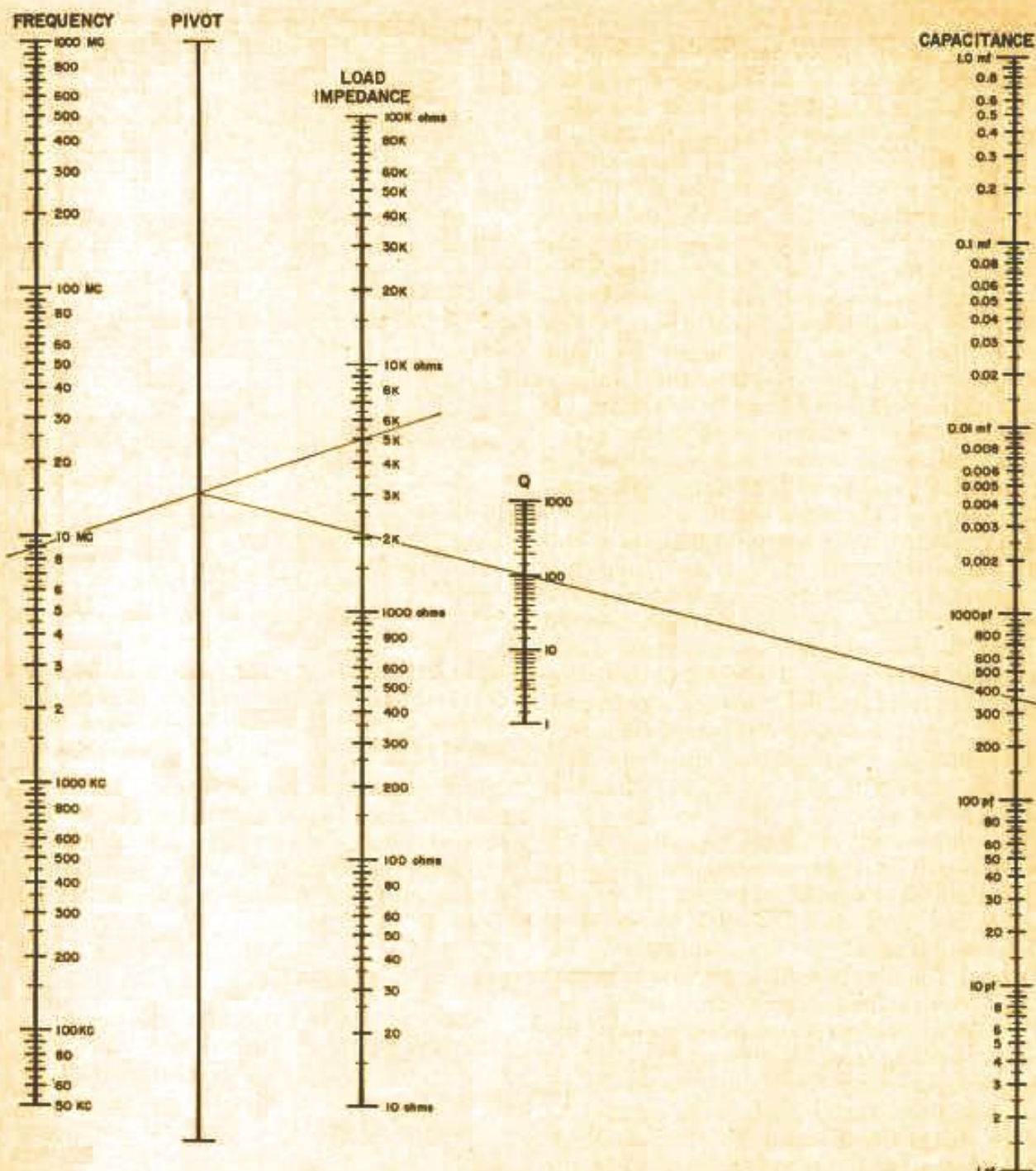
FREQUENCY · PIVOT

| 1000 MC |
| 800 |
| 600 |
| 500 |
| 400 |
| 300 |
| 200 |
| 100 MC |
| 80 |
| 60 |
| 50 |
| 40 |
| 30 |
| 20 |
| 10 MC |
| 8 |
| 6 |
| 5 |
| 4 |
| 3 |
| 2 |
| 1000 KC |
| 800 |
| 600 |
| 500 |
| 400 |
| 300 |
| 200 |
| 100 KC |
| 80 |
| 60 |
| 50 KC |

LOAD IMPEDANCE

| 100K ohms |
| 80K |
| 60K |
| 50K |
| 40K |
| 30K |
| 20K |
| 10K ohms |
| 8K |
| 6K |
| 5K |
| 4K |
| 3K |
| 2K |
| 1000 ohms |
| 800 |
| 600 |
| 500 |
| 400 |
| 300 |
| 200 |
| 100 ohms |
| 80 |
| 60 |
| 50 |
| 40 |
| 30 |
| 20 |
| 10 ohms |

Q

| 1000 |
| 100 |
| 10 |
| 1 |

CAPACITANCE

| 1.0 mf |
| 0.8 |
| 0.6 |
| 0.5 |
| 0.4 |
| 0.3 |
| 0.2 |
| 0.1 mf |
| 0.08 |
| 0.06 |
| 0.05 |
| 0.04 |
| 0.03 |
| 0.02 |
| 0.01 mf |
| 0.008 |
| 0.006 |
| 0.005 |
| 0.004 |
| 0.003 |
| 0.002 |
| 1000 pf |
| 800 |
| 600 |
| 500 |
| 400 |
| 300 |
| 200 |
| 100 pf |
| 80 |
| 60 |
| 50 |
| 40 |
| 30 |
| 20 |
| 10 pf |
| 8 |
| 6 |
| 5 |
| 4 |
| 3 |
| 2 |
| 1 pf |

Fig. 8. Nomograph to determine the required tuned-circuit capacitance when frequency, circuit Q and load impedance are known. First the frequency of operation and load impedance are plotted. A straight line is then drawn from the cross-over point on the pivot line through the required value of circuit Q to find the necessary tuned-circuit capacitance. In the example illustrated, a 9 MHz oscillator with a 5000-ohm load impedance and circuit Q of 100 requires a 355 pF capacitor. In addition to its use in oscillator design, this nomograph may also be used when designing rf and if amplifiers, transistor or vacuum tube.

of tank capacitance.

For example, let's assume that you want to build an oscillator at 9 MHz with a circuit Q of 100; the load impedance is chosen to be 5000 ohms. From the nomograph, plot a straight line between 9 MHz on the frequency scale and 5k on the load impedance scale; note where this plot crosses the pivot line. Now plot a line between the cross-over point on the pivot line and 100 on the Q scale to find the required value of capacitance; in this case about 355 pF. To find the value of inductance that resonates with 355 pF at 9 MHz, use the nomograph of Fig. 6.
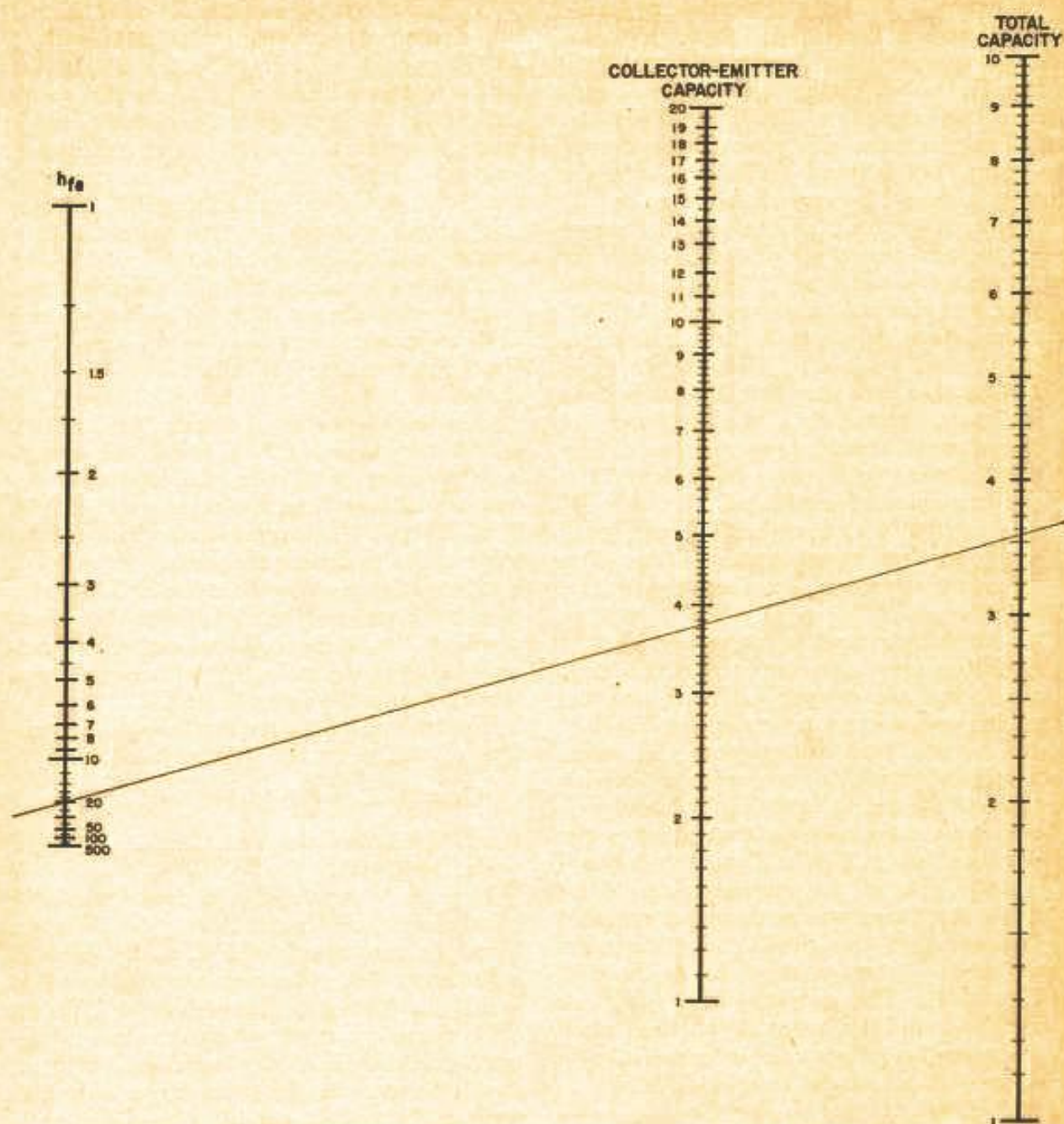
Before we can go any further, we must

hfₐ

COLLECTOR-EMITTER CAPACITY

TOTAL CAPACITY

Fig. 9. Nomograph to find the required collector-emitter capacitor in a transistor Colpitts oscillator when the forward current gain (h$_{fe}$) and total tuned-circuit capacitance (C$_T$) is known. In this case, forward current gain of 20 and total tuned-circuit capacitance of 355 pF requires a collector-emitter capacitor of 375 pF.

determine the impedance of the tuned circuit at resonance. For maximum power again, the tank impedance should be equal to the transistor output impedance; this may be found from

$$Z = \frac{V_{ce}^2}{2P_o} \text{ or } \frac{V_{ce}^2}{I_c}$$

where P$_o$ is the output power, V$_{ce}$ is the voltage between collector and emitter, and I$_c$ is the collector current. In practice a value in the range from 1500 to 5000 ohms is usually used.

The only other consideration is what transistor to use. Theoretically, the oscillator transistor only requires a gain of one or unity, but in practical circuits the gain must be greater than unity because if it were not, aging of the components would eventually result in discontinuance of the desired waveform because of gain reduction. The minimum excess gain that will assure starting is usually about 50 to 100 percent for ordinary circuits. When the gain is greater than one,

more signal is fed back than was originally present, and a buildup in signal level results; however, this increased signal will always be limited by the inherent nonlinearities in the transistor. These nonlinearities will result in some distortion of the output waveform, but in good oscillator design the distortion should be very slight.

Now that we have all the information we need, we can design a Colpitts oscillator for any frequency we desire. Perhaps the best approach at this point is to lay out a "recipe" that will provide us with the desired results:

1. Choose a transistor that has an f_T several times greater than the frequency of operation; it should have a value of forward current gain (h_{fe}) of at least 5 at the frequency of oscillation.

2. Design a bias network which will result in the desired operating conditions. Use the manufacturers recommended operating point.

3. With the operating frequency, desired load impedance and required circuit Q in mind, find the proper value of tank capacitance from the nomograph in **Fig. 8**.

4. The total tank capacitance (C_T) found in step 3 is equal to the equivalent capacitance of C_1 and C_2 in series. These capacitors must have a ratio that satisfies the equation $h_{fe} > C_2/C_1$. Since the forward current gain of the transistor should be about five times greater than that required for oscillation, this condition is satisfied if we use a *starting* value of h_{fe} in choosing C_1 and C_2. The *starting* value of h_{fe} is simply found by using ⅕ of the actual transistor h_{fe} in our calculations. This will ensure an adequate margin of safety in our design.

When the total capacitance (C_T) and *starting* h_{fe} are known, the value of the collector-emitter capacitor (C_1) may be found from the nomograph of **Fig. 9**. Then the required value of emitter-base capacitance (C_2) may be calculated by multiplying C_1 by the *starting* h_{fe}.

5. From the nomograph of **Fig. 6** choose a value of inductance that will resonate with the total capacitance at the desired operating frequency.

This recipe may seem to be a little complex at first, but as soon as you use it, you will find that it is really pretty simple; all the drudgery is removed by the three nomographs.

To illustrate the use of the Colpitts' recipe, let's design an oscillator for 9 MHz with a 2N918 transistor. At 10 MHz the 2N918 has a gain of about 20, so we can use this value at 9 MHz. A check with the manufacturer's spec sheet shows that 1.5 mA collector current (I_c) and 7.5 volts collector-emitter voltage (V_{CE}) is a good operating point. A nine-volt power supply, a 1000-ohm emitter resistor, a 2200-ohm stabilization resistor and a 6800-ohm base-bias resistor will satisfy the biasing requirements (**Fig. 10**). The required load impedance can be found from $Z = V_{CE}/I_C$; in this case 7.5 volts/1.5 mA = 5000 ohms.

Choosing the value of circuit Q to be 100, a load impedance of 5000 ohms and operating frequency of 9 MHz, the total tank circuit capacitance from the nomograph of **Fig. 8** is 355 pF. To insure starting, use ⅕ the value of h_{fe} in finding the values of the feedback capacitors; since the value of h_{fe} in this case is 20, use a value of 4. From the nomograph of **Fig. 9** the collector-emitter capacitor (C_1) is found to be 444 pF; use the next largest standard value, 470 pF.

The emitter-base capacitor is found by multiplying 444 pf by the *starting* h_{fe}, 4:

$$C_2 = h_{fe}C_1 = 4 \times 444 = 1756 \text{ pF}$$

Here again use the next largest standard value, 1800 pF.

Now that the feedback capacitors have been chosen, all that is left is the inductor. From the nomograph of **Fig. 6**, the value of inductance that will resonate with 355 pF at 9 MHz is 0.84 μH. This will be a little bit off because we used standard values of capacitance, but if a slug-tuned coil is used, it will compensate for these larger values as well as the output capacitance of the transistor and any stray capacitance introduced
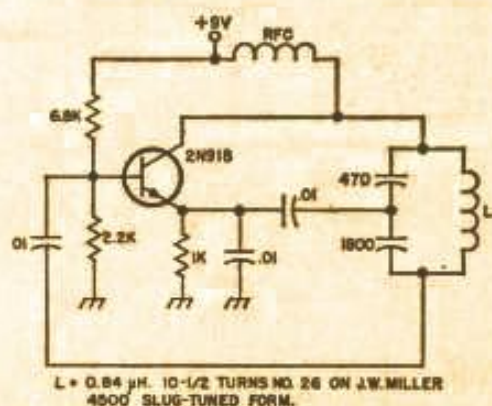

L = 0.84 μH. 10-1/2 TURNS NO. 26 ON J.W. MILLER 4500 SLUG-TUNED FORM.

Fig. 10. Practical 9 MHz Colpitts oscillator designed with the procedure outlined in the text.

by wiring.

The completed circuit is shown in **Fig. 10.**
When this circuit was constructed on the
bench, it started oscillating as soon as power
was applied. The collector current was 2 mA
and the collector to emitter voltage was 7
volts—very close to the desired operating con-
dition. The frequency could be tuned from
8.7 to 11.6 MHz by tuning the slug-tuned
coil. The output voltage, measured at the
collector with a VTVM and rf probe, was
4.4 volts peak to peak.

Hartley oscillator

The Hartley oscillator in **Fig. 11** and **12**
differs from the Colpitts in that the capac-
itors in the Colpitts circuit are replaced by
two magnetic-coupled inductors in the Hart-
ley configuration, and the inductor is re-
placed by a capacitor. The behavior of the
Hartley circuit differs in one significant way
from that of the Colpitts; if the magnetic
coupling between the two sections of the
inductor is relatively high (it usually is),

Fig. 13. The two-winding version of the Hartley
oscillator. In this circuit the necessary phase re-
versal is obtained by connecting the transformer as
shown by the dots.

Fig. 14. Another version of the two-winding Hart-
ley oscillator. In this case, since the drive is applied
to the emitter, no phase reversal is required and
the transformer is connected as shown.

then transformer action can be utilized to
obtain the required current gain to the out-
put of the circuit. Consequently, smaller
values of Q-factor can be used for the tuned
circuit without loss in circuit efficiency.

In most cases the loading of the Hartley
circuit is relatively unimportant as long as
the coupling coefficient between the two
windings on the inductor is high. If the
coupling coefficient is small, then the cir-
culating current in the tank must be large
compared to the load current (implying light
loading) as is the case with the Colpitts

Fig. 11. The basic Hartley oscillator without bias
resistors and power supplies. The circuit may be
further simplified as shown by substituting resistors
Z_t and Z_L for circuit loading by the transistor.
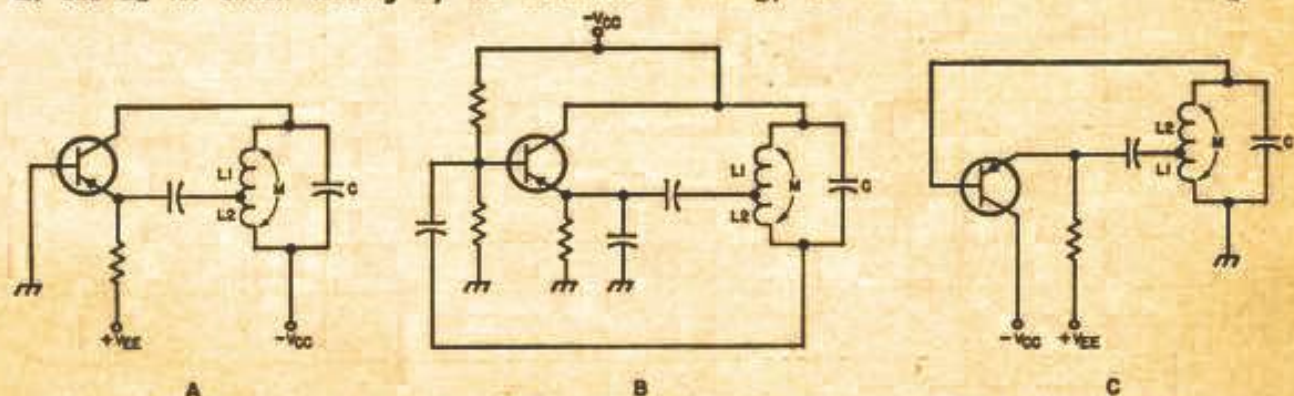
Fig. 12. Practical transistor Hartley oscillators. The common-base configuration is shown in A, the com-
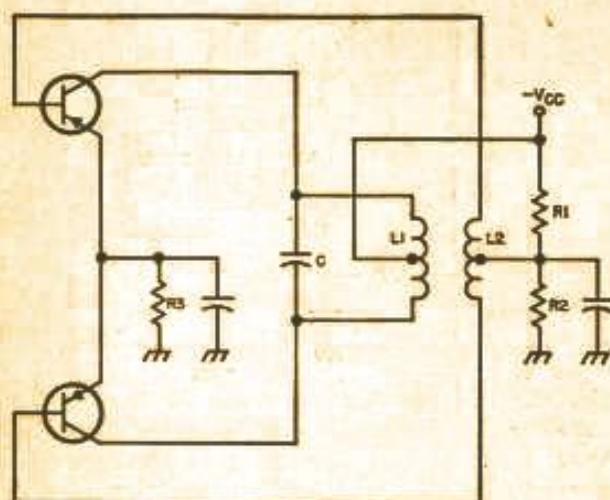mon-emitter in B and the common-collector in C.

Fig. 15. Push-pull Hartley oscillator. This circuit may be designed for greater power and less harmonic output than single transistor circuits.

oscillator.

Although the inductance in the Hartley circuit is usually a tapped coil, a transformer with separate primary and feedback windings may be used. This particular arrangement allows an additional degree of flexibility in that it is possible to obtain the dc bias from the collector supply *or* from a separate dc source. For higher power

output and greater efficiency, the Hartley circuit may be readily modified for push-pull operation by providing center-tapped primary and feedback windings on the transformer. In **Fig. 15** oscillating currents flow in the tank circuit formed by the winding L_1 and the capacitor C_1. Winding L_2 feeds back sufficient energy to the bases of the transistors to maintain oscillation. If the transistors are operated in class B or C, substantially greater efficiency and output power may be obtained than from the single transistor version.

In some respects the design of a Hartley oscillator closely follows that of the Colpitts, but as you might expect, the tap point on the inductor is found in a somewhat different manner. To insure that the Hartley oscillator will start, the value of h_{fe} must be

$$h_{fe} > \frac{L_1 + M}{L_2 + M}$$

In this case, like the Colpitts, the value of h_{fe} used will be about ⅓ the actual h_{fe} of the transistor at the operating frequency.

Unfortunately, this formula contains the mutual inductance factor (M) which is dependent upon the coupling coefficient. And
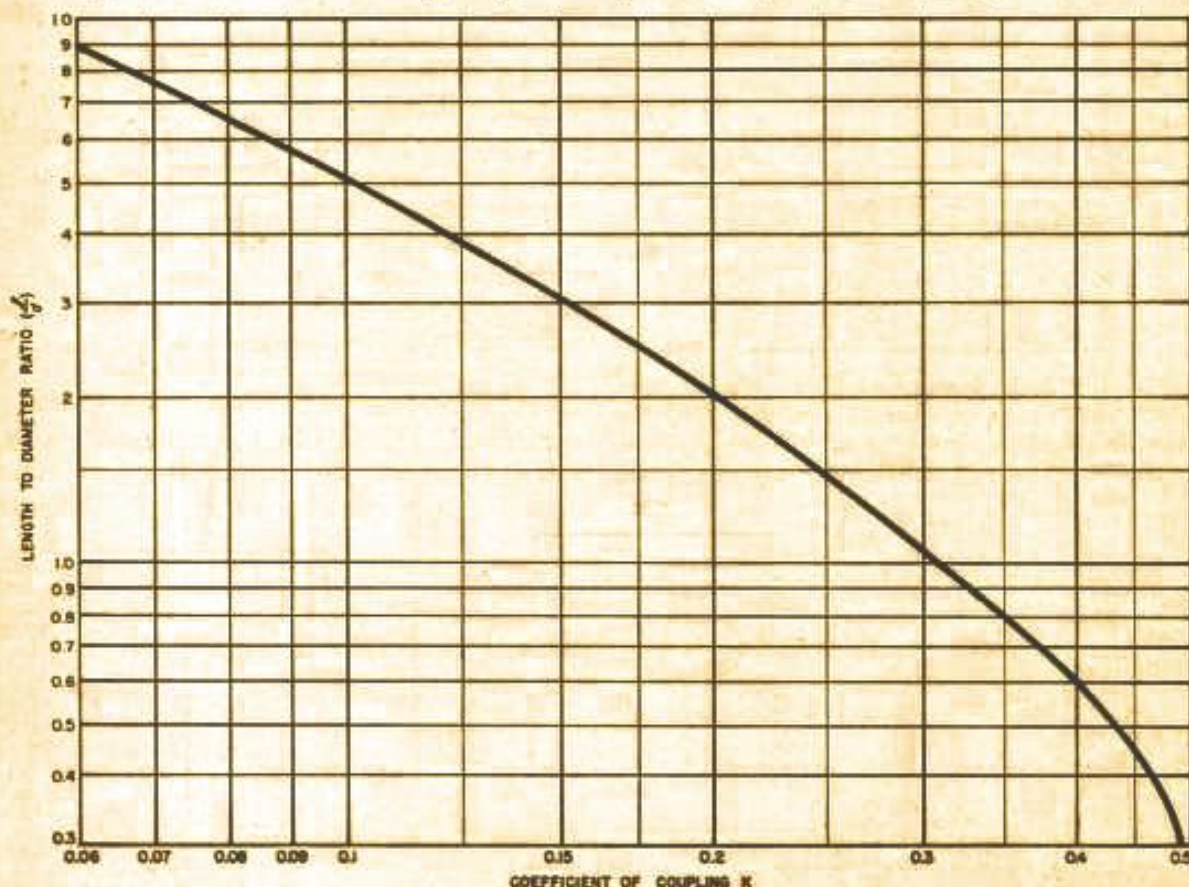

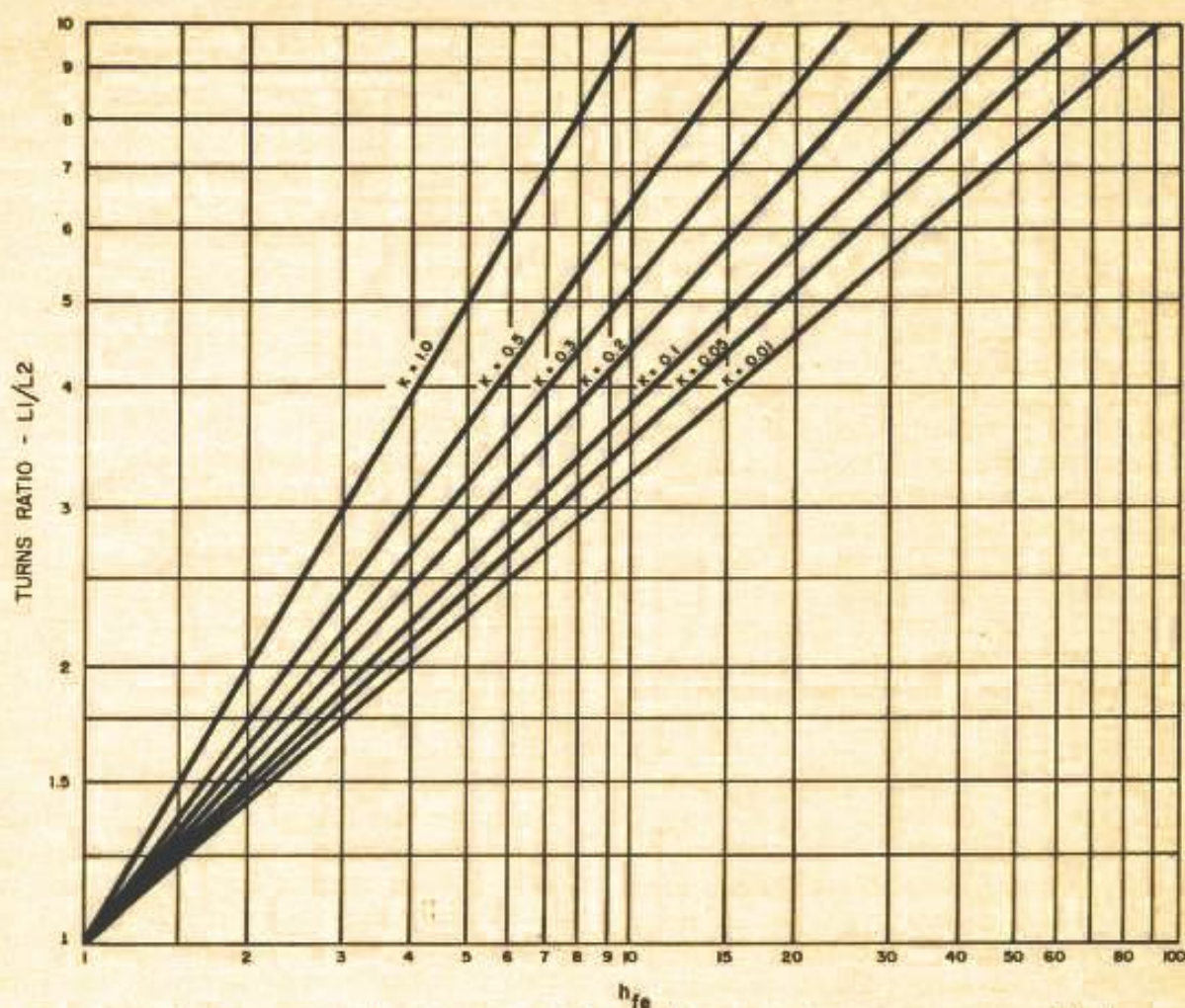Fig. 16. The approximate coupling coefficient (k) of a single wound tapped coil as a function of the coil size.

Fig. 17. Graph for determining the tap point on the tuned-circuit inductor in a transistor Hartley oscillator when the forward current gain (h_{fe}) and coupling coefficient (k) of the coil are known.

—the coupling coefficient is dependent upon the size of the coil and the tap point. Because of all the inter-related dependencies, it's a little tough to come up with the proper tap point on the first try, but by approaching the middle from both ends, the graphs of Fig. 16 and 17 will simplify things.

Once the total inductance is decided upon, the coil can be designed using conventional techniques. When the length and diameter of the coil are determined, the coefficient of coupling can be *approximated* from Fig. 16. With this value of coupling coefficient (k) and the *starting* value of h_{fe}, the necessary turns ratio can be found from Fig. 17. Although both of these curves are approximations, they will get you into the ball park with an operating unit; the oscillator can then be optimized for maximum efficiency and power output.

With these points in mind, we can come up with recipe for the transistorized Hartley oscillator:

1. Choose a transistor that has an f_T sev-eral times greater than the frequency of operation; it should have a value of forward current gain (h_{fe}) of at least 5 at the frequency of oscillation.

2. Design a bias network which will result in the desired operating conditions. Use the manufacturers recommended operating point.

3. With the operating frequency, desired load impedance and required circuit Q in mind, find the proper value of tank capacitance from the nomograph in Fig. 8.

4. From the nomograph of Fig. 6 choose a value of inductance that will resonate with the tank capacitance found in step 3 at the desired operating frequency.

5. Design an inductor that will fit the requirements of step 4; the inductance curves in the ARRL Handbook and the inductance nomograph in the Radio Handbook[3] will eliminate some tedium here.

6. When the length and diameter of the inductor are known, the length to diameter ratio may be calculated and the coupling

coefficient found from **Fig. 16.**

7. The required turns ratio between L_a and L_a may be found from **Fig. 17** by using the coefficient of coupling from step **6** and the *starting* h_{fe}.

As with the Colpitts design, the best way to illustrate the Hartley recipe is to go through a practical example for a Hartley oscillator with a 2N918 transistor at 9 MHz. Since the same transistor is being used, the bias network and total tank capacitance and inductance will be identical to the Colpitts oscillator we previously designed. In this case, however, we have to design the inductor before we can proceed. By scanning the data sheet, we find that 10¼ turns of number 26 enameled wire on a J. W. Miller 4500 form will pretty closely put the target value of 0.84 μH midway in its range. Since the total length of the coil may be found by multiplying the wire diameter times the number of turns, and number 26 enameled wire is 0.017 inches in diameter (from the wire table in the ARRL Handbook), the length of the completed coil will be 10.5 x 0.017 = 0.170 inches.

The diameter of the Miller 4500 coil form is 0.260 inches, so the length to diameter ratio is 0.179/0.260 or 0.69. From the graph of **Fig. 16** a 1/d ratio of 0.69 provides a coefficient of coupling of approximately 0.35. From **Fig. 17** a 0.35 coefficient of coupling and *starting* h_{fe} of 4 indicate a turns ratio between L_a and L_a of 2.6.

This turns ratio and the total number of turns may be used to find the tap point on the inductor. To find the number of turns in L_a, simply add one to the turns ratio (which gives 3.6 in this case) and divide this factor into the total number of turns. In this example L_a = 10.5/3.6 = 2¾ turns.
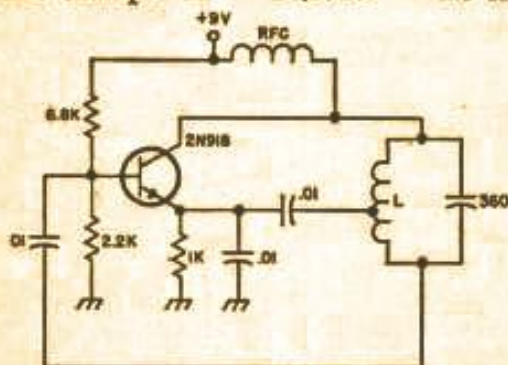
Inductor L_a is the rest of the coil—7¾ turns.

The completed circuit is shown in **Fig. 18.** Like the Colpitts circuit, this oscillator took off as soon as the nine-volt supply was connected. The desired operating condition was very close to that required—V_{ce} of 7.2 volts and I_c equaled 1.8 mA. The output voltage, at the collector, was 3.8 volts peak to peak and the tuning range was almost identical to the Colpitts circuit previously constructed —8.6 to 11.5 MHz.

Clapp oscillator

Another popular oscillator circuit is the series-tuned Colpitts or Clapp circuit shown in **Fig. 19.** This circuit is especially useful to the amateur because in practice it is susceptible to less drift. This is because the tuned-circuit capacitors C_1 and C_2 may be made so large that they swamp out the effects of element capacitance in the transistor. The large values of capacitance also tend to minimize harmonics, further increasing frequency stability.

No recipe for Clapp oscillator design will be given, because in practice the design very closely follows that of its parent, the Colpitts. Usually the values of C_1 and C_2 are so large that the resonant frequency of the circuit is determined primarily by the value of C_3. Since the capacitors C_1 and C_2 govern the amount of feedback, their ratio may be found by using the procedure outlined in step 4 of the Colpitts recipe. The value of C_3 may be found from the nomograph in **Fig. 8,** and the inductance, from **Fig. 6.**

Since the Clapp oscillator is usually used in a VFO, capacitor C_3 is a variable. This is the tough part—to choose a combination of inductance and capacitance (C_3) that will cover the desired range. Although this can
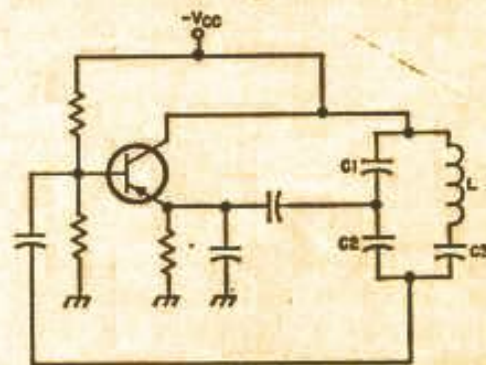

L = 10-1/2 TURNS NO. 26 ON J.W.MILLER 4500
SLUG-TUNED FORM. TAP 2-3/4 TURNS .
FROM BOTTOM

Fig. 18. Practical 9 MHz transistor Hartley oscillator designed with the procedure described in the text.

Fig. 19. The transistor Clapp oscillator. Excellent frequency stability can be obtained with this circuit because the capacitors C_1 and C_2 may be made large enough to swamp out any capacitive effects of the transistor.
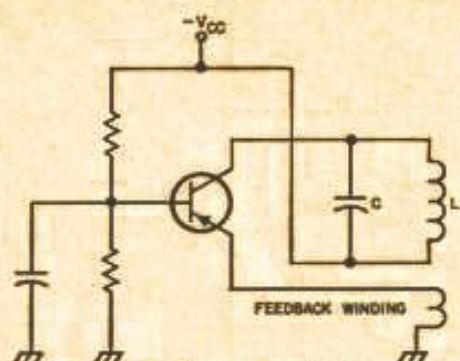
Fig. 20. A tuned-collector oscillator with a feedback winding to the emitter.

be given mathematically, the resulting formula is long and drawn out.[4] The best approach is to design for the center of the required frequency range, and then juggle the values of L and C_a to exactly what you want. If you use a value of C_a which is slightly smaller than what your calculations call for, a padding capacitor can be placed in parallel with it to provide the necessary capacitance adjustments.

Other oscillator circuits

In addition to the Hartley and Colpitts circuits, there are obviously many different ways to satisfy the condition for oscillation. In the tuned-base tuned-collector oscillator
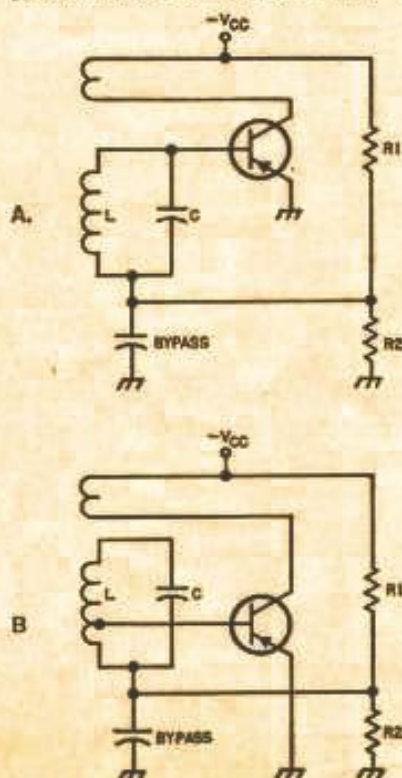
Fig. 21. A tuned-base oscillator with feedback from the collector winding. A better impedance match to the base of the transistor may be obtained by using the tapped inductor as shown in B.

for example, a series LC combination is inserted in both the base and collector leads, which together form the necessary resonant circuit. Fig. 20 shows an oscillator with the tank circuit connected between the collector and base with feedback taken off the tank circuit by the in-phase feedback winding and applied to the emitter.

In the circuit in Fig. 21, the tuned tank circuit is placed between the base and emitter (through ac ground) and out of phase feedback picked up from the collector winding. In Fig. 21B a better impedance match to the base of the transistor is obtained by tapping down on the tuned-circuit inductance.

Most of these simple circuits have one very serious disadvantage—the frequency of oscillation is very dependent upon the collector resistance of the transistor. There is some dependence on the transistor characteristics in all oscillator circuits, but in the circuits of Fig. 20 and 21, the influence of the transistor predominates.

Colpitts or Hartley?

One of the big questions that invariably arises is what circuit to use in a specific application. In many cases the Clapp oscillator is chosen, particularly for VFO's, because in practice stability is somewhat easier to obtain. For other applications though, both the Hartley and Colpitts find favor. Between these two the choice is more difficult. However, as a rule of thumb, the Hartley is more satisfactory at the lower frequencies, while the Colpitts works best in the high-frequency and VHF range. The reasons for this are quite complex, but they can be explained fairly simply with a couple of block diagrams.

In all transistor oscillators where the tuned circuit is connected between the collector and emitter, the feedback network may be represented by X_a, X_b and X_c as shown in Fig. 22. Neglecting circuit losses, the only way that the voltage across Z_1 (the base input impedance) can be precisely 180° out of phase with Z_L (collector impedance) is for the reactance X_a to be opposite from the reactances X_b and X_c and for X_a to be equal to the sum of X_b and X_c. In the Colpitts oscillator X_b and X_c are inductors and X_a is a capacitor. When the circuit losses are neglected, at resonance the input impedance of the feedback network in Fig. 22A appears as an infinitely large resistance.
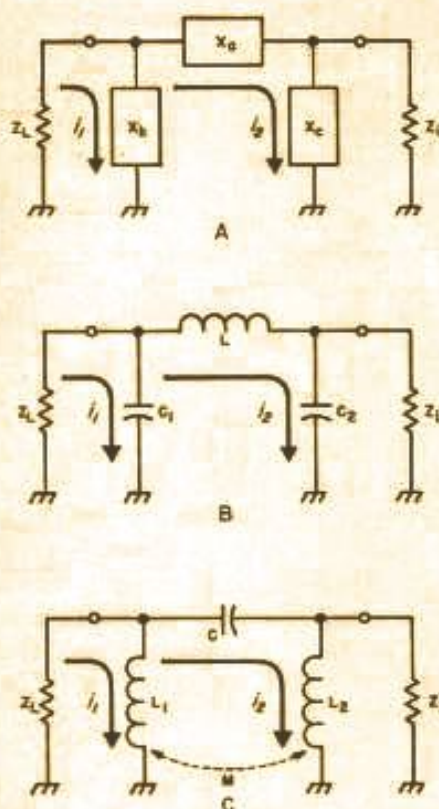
Fig. 22. The current flow in the feedback paths of the Colpitts and Hartley oscillators is shown in B and C. The general case is illustrated in A.

However, in a practical circuit there is base loading, series resistance in the tank coil, loading due to power being coupled from the circuit and the impedance is *not* purely resistive. In a practical Colpitts oscillator for example, the feedback circuit would be represented as shown in **Fig. 22B**; Z_L is the output impedance of the transistor, while Z_i is the input impedance. In this circuit currents i_1 and i_2 are not exactly the same magnitude or of opposite phase as in the ideal lossless circuit. The loading of the base circuit (Z_i) causes the current i_2 to *lag* the collector driving voltage across Z_L by less than 90°; hence the base driving voltage *lags* the collector driving voltage by something less than 180°.

On the other hand, in the Hartley circuit represented in **Fig. 22C**, the base loading causes the current i_2 to *lead* the base driving current by less than 90° and therefore the base driving voltage *leads* the collector voltage by less than 180°.

In the Hartley oscillator the effect of circuit losses and transit times are accumulative, but in the Colpitts circuit these effects tend to offset one another. The fact that the base driving voltage through the Colpitts feedback circuit lags the collector voltage par-
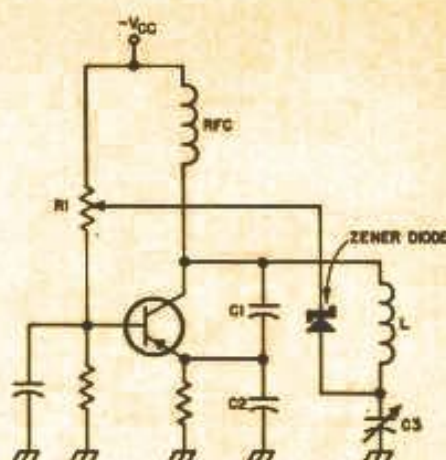

Fig. 23. Connecting a zener diode across the tank circuit of a Clapp oscillator to obtain output stability.

tially compensates for the effects of transit time. For this reason the Colpitts oscillator is somewhat superior to the Hartley circuit at the high and very high frequencies.

Oscillator requirements

The requirements on any oscillator circuit are varied, but in addition to frequency stability, there are several important characteristics which serve to specify the performance of any particular circuit. Perhaps most important of these are amplitude stability, harmonic content, output power level, efficiency and noise output.

Amplitude stability

It is usually desirable for the output signal to remain constant within certain limits as the transistor and other components age during operation. This is particularly a problem with variable frequency oscillators, but fortunately the output may be stabilized in most cases by one of the techniques described below. Theoretically, the amplitude of the voltages and currents in an oscillator will become infinite unless some limiting action occurs somewhere in the circuit. The nonlinearities which will limit the amplitude of the output in a practical circuit are:

1. Limitation of the available dc voltage or current by the capability of the supply.
2. Nonlinearities in the transistor.
3. Nonlinearities in external loads. This is true because the external loads are often a function of voltage and current; above a certain amplitude their values change so that the condition for oscillation is no longer satisfied.

In any case, the amplitude of oscillation will build up until it is limited by one of these three basic limiting mechanisms.

When the oscillator is designed for high efficiency and the output voltage nearly equals the supply voltage, variations in the supply will cause fluctuations in output power. These fluctuations may be eliminated by stabilizing the supply voltage with a zener diode.

Another technique which is slightly more sophisticated has been successfully applied to variable frequency oscillators (Fig. 23). Here the output is compared to a reference diode and the difference fed back to the transistor. Whenever the ac voltage across the capacitor in this Clapp oscillator exceeds a value determined by the variable resistor R3, the diode conducts a compensating base current and reduces the output amplitude.

Harmonic content

In many applications it is desirable to restrict the output power of the oscillator to one single frequency. In other cases harmonics are desirable for frequency multiplying. There are always certain nonlinearities in an oscillator circuit which give rise to signals as multiples of the fundamental. The harmonic content depends on many factors and is as difficult to control as is stability, but primarily it is dependent upon the non-linearities in the circuit and the filtering action of the tank capacitance. If very low distortion is desired, push-pull operation in a two-transistor oscillator may be advised. On the other hand, nonlinearities may be deliberately used to produce frequency multiplication. This is done by incorporating another tank circuit into the oscillator which is tuned to the desired harmonic.

Output power level

The maximum power output from an oscillator is important in many cases, as well as the maximum voltages and currents available within the limitations of stability and harmonic content. The requirements for frequency stability and harmonic content are closely connected with the power, voltage and current-handling characteristics of the transistor used in the circuit.

The conversion efficiency of the transistor oscillator depends primarily on the class of operation and increases as you go from class A to B to C. However, the circuit must be initially biased somewhere in the active re-

gion to insure that the oscillator will be self-starting. With most transistors, efficiencies of about 50% in class A, 78% in class B and 80-90% in class C may be expected.

A bypassed emitter resistor permits class C operation in a manner somewhat similar to the grid-leak method used with vacuum-tube oscillators. An average voltage builds up across the emitter RC combination that provides reverse bias for the emitter diode. With an initial operating point near cutoff, rising oscillations will first result in clipping at the low-current end of the load line, and eventually the buildup will be limited by the nonlinearities at the high current end; the operating point will eventually lie in the cutoff region.

The efficiency of an oscillator is reduced by the dc losses in the resistors of the bias circuit and is tied in very closely with the required operating point stability and ease in getting the oscillator started. AC losses in the resonant tank also reduce efficiency, and a high *unloaded Q* in the tank circuit is desirable. To obtain high efficiency it is necessary in all classes of operation to utilize as much of the available dc supply voltage as possible, with the peak ac collector voltage being equal to approximately 90% of the supply voltage.

In addition, the output power delivered by the transistor to the tank and load must be high. This means that the load impedance seen by the transistor must be designed to be as close as possible to the matching impedance for the transistor. If the output power from the oscillator is specified, then the supply voltage should be only a few percent higher than the ac voltage swing necessary to deliver the required power into this approximately matched load impedance.

Unfortunately, the requirement for high efficiency will lead to low Q of the *loaded* tank circuit. This may cause poor frequency stability and a compromise must be found.

Noise output

In many applications it is very important to keep the noise power from the oscillator at a minimum. This is particularly true in VHF converters where a minimum of noise should be injected into the mixer.

Noise in the transistor also effects frequency stability—the initiation of oscillation is a result of thermal and other forms of noise shock-exciting the oscillator circuit,

changing the over-all amplification and affecting the phase stability at the same time. Consequently, in oscillators that must meet extreme frequency stability requirements, the transistor must be very quiet at the operating frequency. In addition, the operating conditions should be selected to introduce a minimum amount of noise.

The design of transistor oscillators is not particularly amenable to a paperwork design, followed by building an optimum circuit on the very first try; in all cases the design must be accompanied by some experimental cut and try. The frequency of oscillation, the desired power output, and other requirements, such as frequency and amplitude stability are required with fluctuations in supply voltage and transistor perameters over certain temperature ranges. However, experience has shown that the following general procedure provides best results:

1. Select a transistor capable of the desired power output and exhibiting sufficient gain at the frequency of oscillation.
2. Select the type of oscillator circuit to use.
3. Establish the bias point and design a bias network with the necessary degree of stability. The bias point may be subject to change later to improve efficiency by shifting operation into class B or C.
4. Design the tank circuit using the given formula and design nomographs.
5. Try varying amounts of feedback to optimize efficiency; vary the operating point to achieve class B or even class C operation without sacrificing ease in getting the oscillator started (the emitter junction must not lock in the reverse-biased condition).
6. Use a slug-tuned coil or trimming capacitor to make final adjustment, if necessary, of the frequency of oscillation.

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