VARIABLE-FREQUENCY OSCILLATORS

OSCILLATORS, VARIABLE FREQUENCY

An oscillator is defined as anything that swings back and forth like a pendulum (vibrates) or travels back and forth between two points. An electronic oscillator is a device used for producing alternating current (e.g., a radio frequency or audio-frequency generator). Frequency is the number of times that a periodic function repeats the same sequence of values during a unit of time or the number of complete oscillations of a wave per second.

Oscillators are abundant all around us: light, sound, the rotation of the earth, electric ac power, heart beats, musical instruments, motors, microprocessor clocks, and so on. Some of these oscillatory systems have variable frequency, and some have fixed frequency. We will first describe all the different types of electronic oscillators to appreciate what determines their operating frequency and how it can be varied.

TYPES OF OSCILLATORS

There are two basic kinds of oscillators: sinusoidal and relaxation. The mechanisms that produce these two types of oscillations are different, as are the required conditions for oscillation. RC- and LC-tuned circuits represent sinusoidal oscillations. Their oscillations are continuous and relatively sinusoidal. Relaxation oscillators are represented by multivibrators and ring oscillators. Their oscillations are discontinuous and nonsinusoidal.

Sinusoidal oscillations are created when energy stored in one form is allowed to change uniformly into another form, going back and forth between the two without stopping. Because energy may be transferred between states with minimum loss, some sinusoidal oscillators can be energy efficient because only small amounts of energy need to be supplied externally to keep the action going. This type of oscillator is associated with linear systems. Sinusoidal oscillators are of two types: feedback and negative resistance.

Relaxation oscillations are characterized by the sequential accumulation and release of energy in one or several storage elements. Energy is accumulated up to a certain level (threshold) and then quickly released (usually dissipated as heat), and then another element (or the same element) in the system begins to accumulate energy until the cycle repeats. The action exhibits positive feedback during reset or relaxation, reinforcing itself and occurring rapidly. This type of oscillator is associated with nonlinear systems. Because all the accumulated energy is periodically dissipated, relaxation oscillators are very energy inefficient.

This article does not cover chaotic oscillators. Chaotic oscillators do not have a periodic sequence of events that repeat in a unit of time. Related to nonlinear systems, chaotic oscillators occur for example in turbulent flows of liquids or in noise-like random signals generated in certain electronic systems.
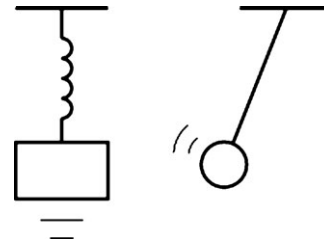

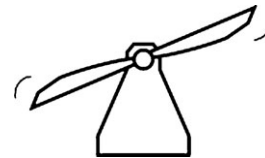**Figure 1.** Simple mechanical damped oscillators.

Figure 2. A windmill produces oscillations of varying frequency in response to the wind force.

MECHANICAL EXAMPLES

The most elementary types of mechanical oscillators are the spring and mass and the pendulum, as shown in Fig. 1. In the spring and mass, the energy is alternately changing from the spring to the potential and kinetic energy in the mass. At the top of its swing, all the energy is potential energy related to the elevation of the mass. Midway down, there is kinetic, potential, and spring energy. The pendulum is a well-known example of the oscillation between potential and kinetic energies.

Both systems will slow down because of the friction in the air. The spring also dissipates energy because of the internal friction of its metal grains. The pendulum has friction at the hinge. Rather than being strictly oscillators, these mechanical arrangements are examples of damped oscillators. An energy input is necessary to compensate for the losses and to deliver power to outside "loads," for example to synchronize other mechanical devices.

The windmill is an interesting example of an oscillator (Fig. 2). Its frequency is proportional to the drive level (e.g., the wind strength). The amplitude of the oscillation is, however, fixed. This is the opposite of electronic oscillators, which increase their signal swing in response to more supplied power. However, if we think of the windmill as driving a load, like an ac voltage generator, then there is a relationship between its energy output and the available wind energy. The paddles seem to rotate with the same "magnitude," but they deliver changing amounts of energy at varying frequencies.

An example of an oscillatory system that is not sinusoidal, like the pendulum or the windmill, is shown in Fig. 3. The water drops accumulate in the glass until the surface tension can no longer hold any more liquid, the water spills over the edge, and the cycle repeats. It is called a relaxation oscillator because the energy accumulates in a certain form up to the level that causes the system to relax and let go of the accumulation; then the system resets and restarts the sequence.

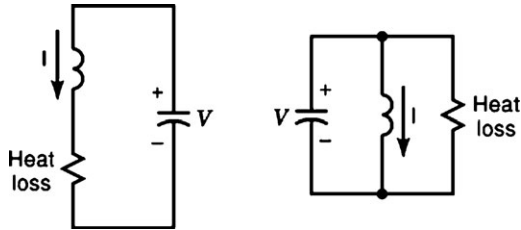**Figure 3.** Mechanical example of a relaxation oscillator.

Figure 4. Electrical damped oscillatory systems: series and parallel resonators with loss.

ELECTRICAL RESONATORS

The electrical equivalents of the mechanical resonator are the series and parallel resonant "tanks" shown in Fig. 4. They are composed ideally of just an inductor and a capacitor, but there are always losses that are modeled by resistors. The energy is alternatively stored in the capacitor (as an electric field of potential energy) and in the inductor (as magnetic energy). When the capacitor is at full charge, the voltage across the parallel arrangement is at its peak; and when the current through the inductor is at its peak, then the voltage across the tank is zero.

Other popular resonators are transmission line, Dielectric, Yttrium-Iron-Garnet (YIG), Crystal, and Surface Acoustic Wave (SAW). Resonant tank equivalent circuits at different frequencies of operation can represent all of these.

QUALITY FACTOR (Q)

The Q of a resonator is a useful number to calculate. It is defined as 2π times the ratio of the energy stored in the system to the energy dissipated per cycle (1). It turns out that Q has two other useful interpretations. It is a measure of how many cycles it takes a damped oscillatory system to decay (2), and it defines the 3 dB bandwidth of a second-order resonator (3). Q also describes how rapidly the phase changes with frequency near the resonant frequency, indicating how little the frequency will shift with changes that affect a delay in an oscillator loop (4). Finally, for a series resonant circuit, Q is the ratio of impedance in L or C divided by R (5); for the parallel resonant circuit, Q is the inverse of this equation.

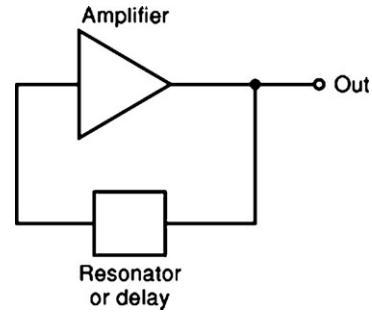$$Q = 2\pi \frac{\text{Peak energy stored in } L \text{ or } C}{\text{Energy dissipated per cycle}} \qquad (1)$$

Figure 5. An oscillator viewed as a feedback system in which the output provides its own input.

$$Q = \pi \, (\text{Number of cycles to decay to } 1/e) \qquad (2)$$

$$Q = \frac{\text{Resonant frequency}}{3 \text{ dB bandwidth of resonator}} \qquad (3)$$

$$Q = \frac{w}{2} \times \frac{d\varphi}{dw} = \frac{w}{2} \times \text{Rate of phase change with frequency} \qquad (4)$$

$$Q = w \frac{L}{R} \qquad (5)$$

SINUSOIDAL OSCILLATORS

Feedback Oscillators

A general way of thinking about an oscillator is in terms of an amplifier that feeds its output back to its own input (Fig. 5). The feedback is controlled by a resonator or a delay element in such a way that the desired frequency and amplitude of oscillation are achieved. Note that the resonator or delay box is still indicated as a two-terminal box with another two-terminal amplifying box connected across it. This could be viewed as a negative resistance oscillator, as will be discussed later.

Conditions For Oscillation

Normally, for oscillation to start, the active device provides more energy than is being dissipated in the resonator. This causes the amplitude of the oscillation to grow until it is limited by changes in the active device that reduce its gain. The losses in a system may be linearly related to its amplitude over a limited region, but they grow more rapidly (nonlinearly) over an extended region of amplitude, until they eventually hard limit the amplitude (e.g., when a barrier is reached).

The requirements for oscillation are that the amplitude of the signal being fed back be large enough to produce an output that can reproduce the feedback (greater than unity loop gain) and that the relative phase between the input and the fed-back input be near zero (so the feedback reinforces the output). More simply said, the one-way trip around the loop needs to have gain greater than one and zero phase. However, these conditions should not be met at dc; otherwise, the oscillator will latch into a limit state,
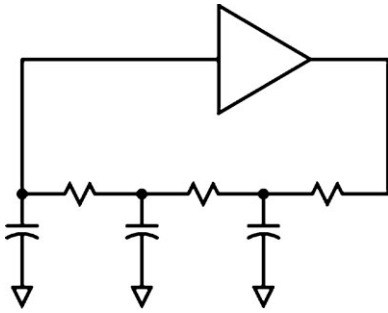
Figure 6. *RC* delay oscillator. For an inverting amplifier, there must be 180° of phase shift in the *RC* feedback path.

and no ac oscillation will develop. Additionally, stable oscillations develop only if disturbances in amplitude or phase cause the oscillator to respond by moving back to the unstable point. Finally, reliable oscillators need to have only one frequency at which the conditions for oscillation are met; otherwise, frequency jumps could occur.

Rc Delay Oscillator (Phase Shift Oscillator)

The circuit shown in Fig. 6 is known as the *RC* (resistor-capacitor) delay oscillator. Three stages of *RC* delay are used in the feedback path. If the amplifier is inverting, then the *RC* network needs to produce 180° of phase shift at the frequency of oscillation. Stated differently, the oscillation will occur at that frequency at which the feedback has a phase delay of 180° and the gain is greater than one. Other possibilities to realize the phase delays are to *RL* (resistor-inductor) delay or lossy transmission line delay. A transmission line is just a distributed *RLC* delay element. *LC* delay elements and lossless transmission lines will be covered next.

LC-Tuned Oscillators

When a tuned circuit is used to define the oscillation frequency, it is desirable to preserve its frequency selective properties *Q*. To prevent loading a resonator by the input of an amplifier, a transformer is necessary. Several types of impedance transformation are possible by using coupled inductors, inductive division, or capacitive division. Another possibility is to use another amplifier as a buffer: the input impedance of the buffer is high, and the loading on the resonator is light.

Figure 7 shows two ways of looking at how an amplifier can be connected across a tank circuit using capacitive division of voltage. The arrangement shown on the right is known as the Colpitts circuit. Capacitors C_1 and C_2 in series form part of the resonator, and the input loading by the amplifier is reduced by their ratio. The circuit on the left uses the capacitors as a way of getting 180° of phase shift at resonance, while internally completing the loop with an additional 180° resulting from signal inversion. However, the two capacitors are still connected in series to each other and across the inductor, and voltage division takes place across this tank. The advantage of capacitive division over inductive division is that it is easier to realize in an integrated circuit. Split inductors or transformers are more

complicated to build than simple inductors.

The arrangements shown in Fig. 8 are known as Hartley and Armstrong oscillators, respectively. The feedback in the Hartley circuit is provided by inductive division, using two inductors or a single inductor with a tap connection. Inductive division, using two inductors or a single inductor with a tap connection, provides the feedback in the Hartley circuit. The input loading is therefore decreased. The Armstrong circuit uses two inductors, L_1 and L_2, with inductive coupling between them. This may be attractive if the objective is to keep the input and output biases isolated from each other. Moreover, the amount of coupling between the coils can be varied without changing the values of the inductors.

A single transistor implementation of the capacitively divided tank circuit is depicted in Fig. 9. This circuit is simple because the base bias is provided through the inductor. The value of the collector load resistor needs to be large enough to prevent decreasing the *Q* of the resonant circuit. The coil and the series connection of the two capacitors make up the resonant circuit. This arrangement can be modified by placing a capacitor in series with the coil (and providing base bias). The series resonant frequency of the coil and the added capacitor can dominate the oscillation frequency, making the circuit less sensitive to variations in the transistor and in the other two capacitors. This modification is known as the Clapp oscillator.

The dc-coupled *LC* oscillator in Fig. 10 is based on a differential amplifier. It has a single-ended tank and a single-ended output. Its output is directly coupled to its noninverting input, and therefore the feedback needs to provide 0° of phase delay because 360° would be impossible with the circuit shown. At resonance, the *LC* tank presents a purely resistive load to the collector output, and therefore it has no phase delay. Any internal delay through the device will need to be canceled by adjusting the oscillation frequency slightly out of resonance. The frequency of this oscillator would normally be controlled by using a variable capacitor. Using a variable capacitor would normally control the frequency of this oscillator. A small change in frequency can also be obtained by changing the bias on the differential amplifier.

Tuned oscillators may also use transmission lines, cavities, dielectric resonators, crystals, or YIG resonators to determine their operating frequency. These resonators have equivalent circuits of very high *Q*. For example, because of the interaction between voltage and mechanical resonance, piezoelectric quartz crystals are much more stable and of higher *Q* than *LC* resonators.

Use of Varactors

Varactors are used to vary the frequency of resonant *LC* circuits (Fig. 11). The combined symbol of a capacitor with a diode arrow is used to indicate that they are diodes that vary their junction "depletion" capacitance. This happens in response to a change in the reverse voltage applied across them. The types of varactor diodes that have the most change of capacitance with voltage are named hyperabrupt. The junction between the *n*-region and the *p*-region is made very sharp, and the doping concentrations
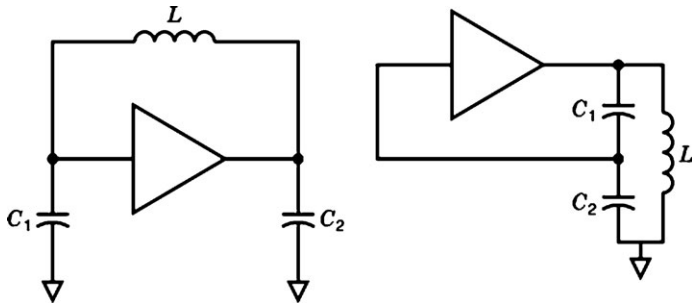
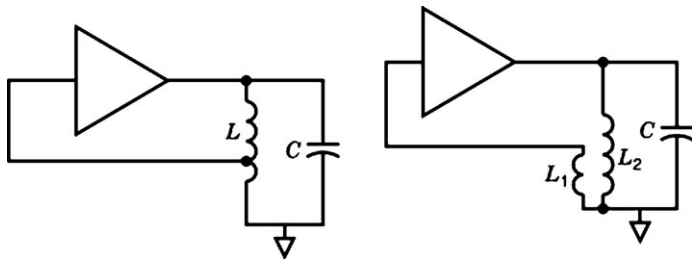**Figure 7.** Oscillators with capacitive division of voltage, also known as Colpitts arrangements.

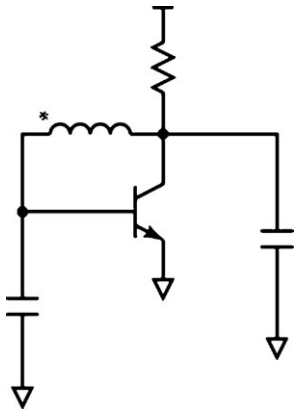**Figure 8.** Inductive division of voltage in Armstrong and Hartley oscillators.

Figure 9. Single-transistor implementation of a capacitive division oscillator.

Figure 10. Differential amplifier LC-tuned oscillator with single-ended output. The emitter follower provides dc-coupled impedance transformation.

are very different. This causes the depletion layer on the lightly doped side to move considerably with applied voltage. Since varactors also have loss, they must be selected or designed to minimize the degradation of the resonator's Q.

The drawing on the left side of Fig. 11 shows a common back-to-back connection of two varactors. Because the voltage that develops in a tank circuit is large, this arrangement offers some cancellation of the variation of the capacitance as a function of the tank voltage. Even order distortion products are canceled, and the voltage at which the diodes would conduct is increased. The simpler arrangement on the right requires a capacitor to ac couple the varactor to the inductor so that the bias voltage is not shorted out by the inductor. This circuit is adequate when the signal level is small or when there is no concern about generating harmonics of the tank's fundamental frequency.

Negative Resistance Oscillators

Negative resistance oscillators also can be viewed as one-port oscillators, as opposed to the two-port oscillators used
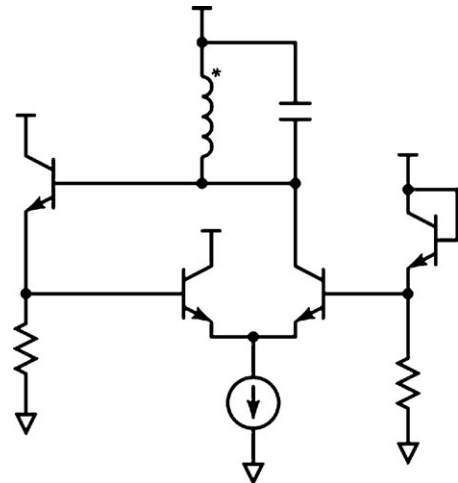
in feedback arrangements. Some electronic devices (e.g., microwave diodes) are two-terminal devices and can be operated only as a one-port device. Therefore, negative resistance oscillator analysis is the most general in that it includes two- and three-terminal (or more) electronic devices.

To compensate for the losses in a resonant circuit, an active circuit needs to supply power to cancel them. This can be thought of as paralleling the resonator with a negative resistor (Fig. 12). It turns out that most oscillator arrangements can be simplified to this type of model, and an equivalent value for negative R can be calculated. If the negative resistance 'black box' is a two-port, which is common, then the other port can be tuned to deliver power to a load.

One possible single-transistor version of a negative resistance oscillator is shown in Fig. 13. The capacitor from emitter to ground makes the input impedance at the base
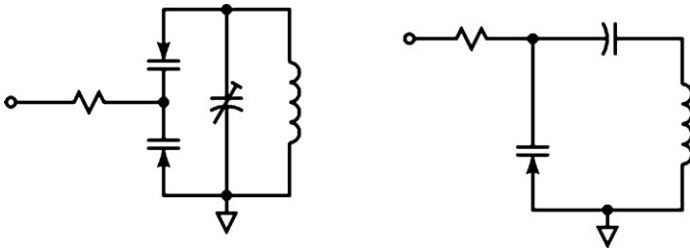
Figure 11. Resonator arrangements using varactor diodes to tune the center frequency.
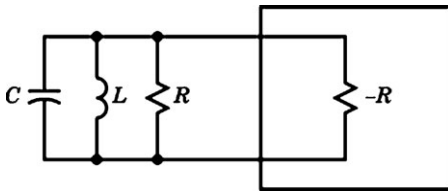

Figure 12. Negative resistance compensates for the losses in a parallel tank resonator.

Figure 14. A ring oscillator consists of a number of buffers connected in a loop.
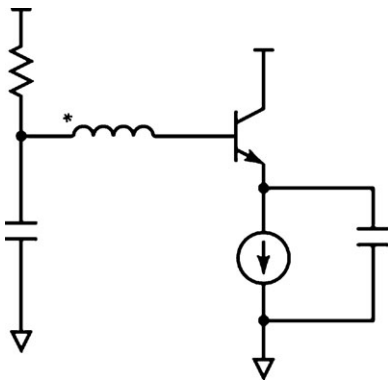

Figure 13. Negative resistance oscillator with series resonant tuning.

partly negative real and partly capacitive. The inductor at the base can be either series or parallel resonated with the input capacitor and with other tuning capacitors or varactors. Note that one could use the collector to deliver power to a load, instead of connecting it to the power supply.

RELAXATION OSCILLATORS

Ring Oscillators

Ring oscillators are a popular topology for variable frequency oscillators used in integrated circuits because they have broad tuning range and require no resonators. They consist of a number of amplifiers or delay stages that may be inverting or noninverting, connected in such a way that an odd number of inversions exist around the loop (Fig. 14). The loop is therefore never "happy," and the result is that an "edge" propagates around the loop. Loops with as little as two buffers are possible, but for large number of stages it is customary to choose prime numbers to prevent the occurrence of multiple modes of oscillation. For example, if we used six buffers, we could have three "edges" running around the loop, with the result that the frequency would sometimes be three times higher. This would happen at
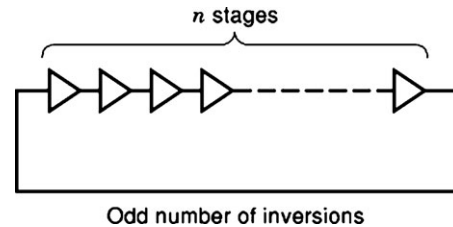
random after powering up the circuit.

The frequency of a ring oscillator can be varied in several ways. One popular way is to change the internal delay of each buffer by adjusting the amount of current available to charge and discharge the circuit capacitances. Another way is to vary the amount of load presented at the output of each buffer.

Astable Multivibrators

Figure 15 shows the main features of an astable multivibrator. It consists of an amplifier with a positive feedback connection that causes hysteresis in the multivibrator. When one of the inputs causes the output to swing in one direction, the positive feedback changes the switching threshold, reinforcing the input so that there is no hesitation if the input begins to change back. It behaves like a comparator with a moving input threshold. This prevents noisy outputs when the inputs are changing too slowly or when they "sit" too close to the threshold. In the case of this oscillator, the hysteresis allows the operation of the circuit, which would not occur otherwise. The R and C connected to the inverting input cause this point to vary exponentially up and down around the hysteresis voltage region. Multivibrators have a broad tuning range.

The astable mutivibrator in Fig. 16 is a popular oscillator circuit that is often built in university engineering laboratories and by hobbyists. It is nonlinear because the two transistors take turns being on and off, without spending much time midway. When transistor Q_1 turns on, its collector pulls the base of Q_2 down, through C_2, keeping it off. Resistor R_3 will in time recharge C_2 and turn Q_2 back on. When this happens, there is positive feedback. As Q_2 turns on, it will turn Q_1 off, and as the collector of Q_1 goes high, it will reinforce Q_2 being on. Next, R_2 will begin to recharge C_1 until Q_1 is turned back on. The RC time constants ($R_2 C_1$ and $R_3 C_2$) need not be the same, and nonsymmetrical oscillations can be designed with this circuit. For example, a narrow pulse can be produced. The frequency of oscillation can be varied by changing the value of the resistors (most
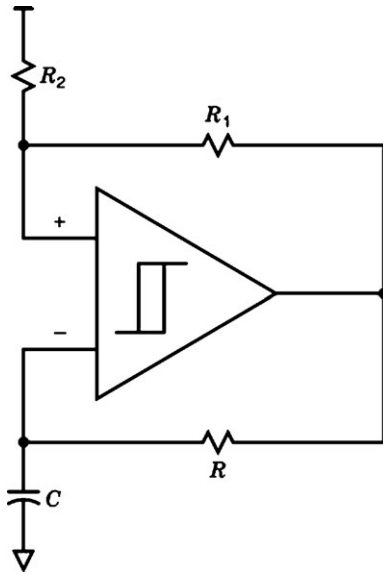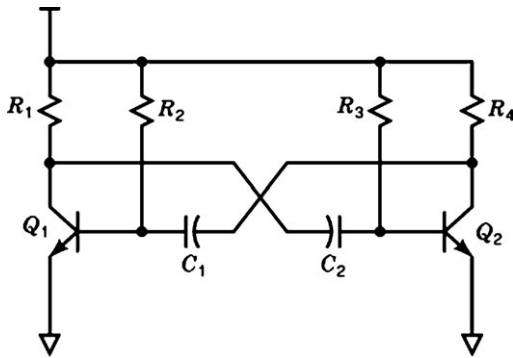
Figure 15. Diagram of a bistable oscillator.

Figure 16. Example of common multivibrator. The system has two stable points: when Q_1 is on and when Q_1 is off (and Q_2 is therefore on).

Figure 17. Another multivibrator or astable oscillator that needs only one capacitor.

commonly R_2 and R_3) or by switching different values for the capacitors and using the resistors for fine adjustment. Other possibilities are changing the power supply voltage or the value of the collector load resistors, which are typically smaller than R_2 and R_3.

Another popular astable multivibrator circuit has a single timing capacitor (Fig. 17). Its frequency is adjusted by changing the value of the current sources. Transistors Q_1 and Q_2 form a cross-coupled pair through Q_3 and Q_4 that acts like an emitter-follower buffer. In this configuration, when one of the two bottom transistors is on, it forces the other transistor off and vice versa, in a "latching" arrangement with large hysteresis. For example, Q_1 being on forces Q_2 off, which reinforces the state of Q_1 being on. The transistor that is on must supply current to both current sources I and therefore will begin to charge capacitor C until the voltage at its own emitter rises and turns itself off. This happens quickly. The other transistor begins to charge the capacitor in the opposite direction, and the cycle repeats itself. The frequency of oscillation is linearly proportional to the value of the current in the sources because the capacitor is charged linearly by current and not
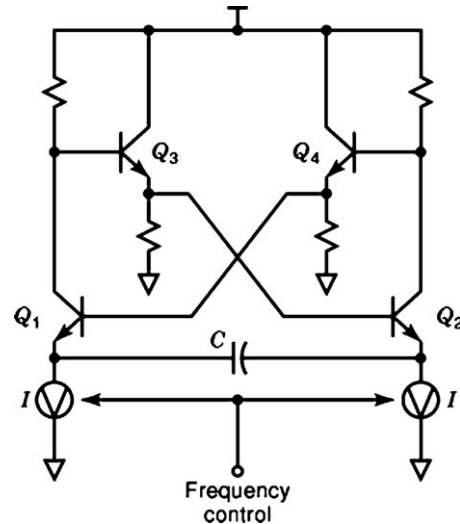
through a resistor. The waveforms at the emitters of Q_1 and Q_2 are linear sawtooth waves.

The Schmitt-trigger oscillator shown in Fig. 18 is also known as the grounded-timing-capacitor oscillator. The differential amplifier and two emitter-followers on the right are connected in positive feedback. When the transistor directly on top of the timing capacitor is turned on, it quickly charges it to near the power supply voltage and forces the "trigger" to switch states. This turns off the top transistor, and the current source begins to discharge the capacitor linearly. When the capacitor voltage is low enough, the trigger switches, and the process repeats. The output waveforms of this oscillator consist of narrow complementary pulses, whereas the voltage across the timing capacitor is a linear sawtooth waveform.

Voltage-To-Frequency Converters

Voltage-to-frequency converter circuits are used not so much to produce oscillations but rather to measure voltages precisely. They achieve linear transfer characteristics from voltage to frequency and allow a frequency counter (a digital circuit of high repeatability) to measure the input voltage level. However, as an example of a variable-frequency oscillator, this is the most linear of all.

In the schematic drawn in Fig. 19, the input voltage V_{in} causes current to flow into the precision integrator circuit containing or including C_i. The comparator with hysteresis periodically switches capacitor C_f from the voltage reference V_{ref} to the input terminal of the integrator, discharging it fully. This achieves the transfer of a measure of charge in a way that is independent of the waveform driving the switch, as long as capacitor C_f is given enough time to discharge fully. Note that the polarity of V_{ref} needs to be opposite that of V_{in}, or the capacitor needs to be discharged inverted. This can be done by connecting the top side of the capacitor to the input, and the switch to the bottom side.
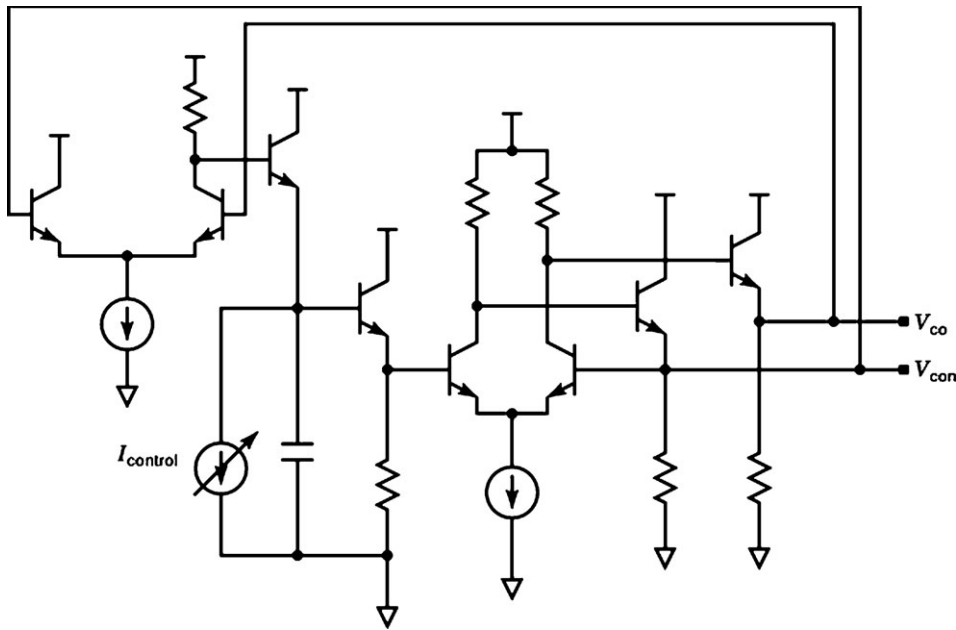
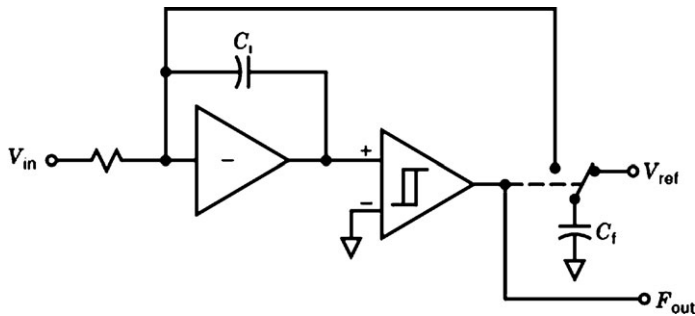**Figure 18.** Detailed schematic of a Schmitt-trigger oscillator with the single timing capacitor tied to ground.

Figure 19. Voltage-to-frequency converters are used to measure voltages.

PROGRAMMABILITY DESIGN STYLES: HOW TO VARY THE FREQUENCY

Most variable-frequency oscillators are voltage controlled (*VCO*s). This is a desirable feature because producing a variable voltage is usually easier than producing a variable current. Even if the frequency control is by variable capacitance, varactors that require a control voltage can be used. In cases where the control variable is naturally current, as in relaxation oscillators or in some ring oscillators, a voltage-to-current converter can be added to make the circuit a V_{CO}.

For sinusoidal oscillators, the presence of a resonant circuit imposes a limited tuning range. Frequency change in these circuits usually uses variable capacitors—or variable resistors in an RC oscillator. In the past, mechanically tuned air dielectric capacitors and even variable inductors were used. Modern designs prefer using varactor diodes. However, the tuning range is limited to less than an octave in a resonant circuit that uses variable components.

To increase the tuning range, different component values can be switched around for different ranges. Usually the inductance is switched, while the capacitance is continuously varied. Mechanical switches have been used in the past, but today switching diodes are preferred because of their small size, lower cost, and higher frequency performance (less parasitics). A popular switching diode is known as *p–i–n*. It consists of three layers of *p*-type (undoped or intrinsic) and *n*-type semiconductors. When no current flows through the *p–i–n* diode, the *i*-layer acts like a thick dielectric, and the diode's capacitance is low. When current is forced through the diode, it exhibits low series resistance. It therefore approximates an ideal switch.

Although their frequency can be varied only over a very small range, crystal oscillators can change frequencies dramatically by switching the crystal element. In some radios, channels are changed by switching crystal values in several oscillators, and their outputs are multiplied or mixed together to produce the desired frequency.

Relaxation and ring oscillators have wide tuning ranges in spite of their poor stability and noise performance. It is easy to tune them over a 10:1 ratio, and with careful circuit design, more than two decades of frequency control are possible. Voltage-to-frequency converters are also easy to tune over broad ranges, although they are relatively slow oscillators.

Table 1 highlights the features of the different oscillators covered. Depending on speed, tuning range, and method of tuning required, a variable-frequency oscillator that meets the required needs can be found. Of course, no single oscillator can simultaneously satisfy all possible needs, and other variables like available materials and cost
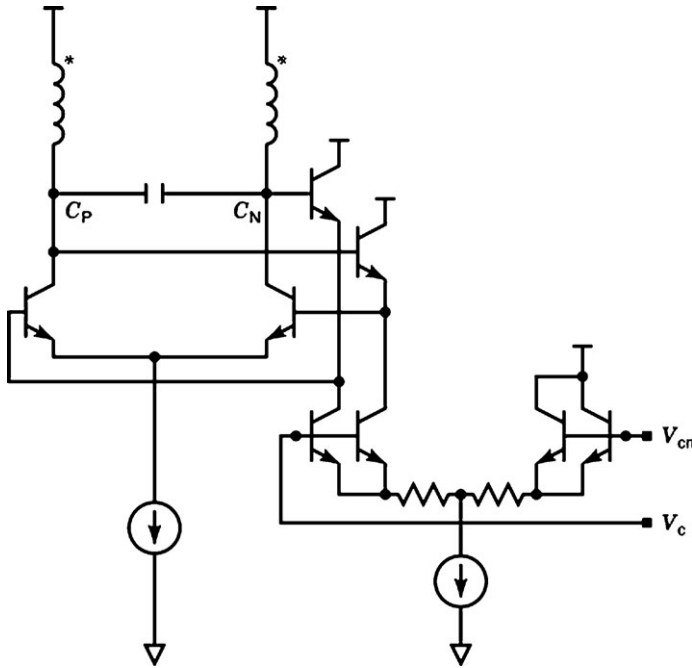
Figure 20. Fully differential *LC* oscillator with delay tuning.

need to be evaluated.

Table 1. Main Features of Variable-Frequency Oscillators

Type	Frequency	Tuning Range	Tuning Means
RC Oscillator	Low to mid	Medium	Resistor or capacitor
LC-tuned oscillator	Mid to high	Narrow	Capacitor, switch inductor
Crystal oscillator	Mid	Very small	Voltage, switch crystals
Ring oscillator	Low to high	Wide	Current or capacitor
Astable multivibrator	Low to mid	Wide	Current
Voltage-to-frequency converter	Low	Very wide	Voltage

ADVANCED CIRCUITS

Further examples of more sophisticated circuits will be described shortly. The first three examples are differential versions of previously discussed arrangements. Their advantages in rejecting power supply noise and in reducing even order distortion more than offset the added complexity. Particularly in integrated circuit design, trading number of components for enhanced response is always a winning strategy. The last circuit shown is an elegant arrangement for a crystal oscillator that has improved output buffering.

A differential *LC* oscillator with delay tuning has frequency control by varying the delay of the feedback signal (Fig. 20). This works well for low *Q* tank circuits that are realized in monolithic implementations. The outputs are directly coupled to the inputs without inversion. The resonant circuit is composed of the series sum of the two inductors and the capacitance across them. The two collectors connected to the tank are operating 180° out of phase. The current at the bottom of the two emitter-followers, that connect to the tank inductors followers, which connect to the tank inductors, is varied to change the oscillation frequency. This is done by using another differential amplifier with two output transistors. Less current results in more delay, which the loop compensates for by lowering the frequency of oscillation. Because of large emitter degeneration, the control voltage produces a near linear change in the current going into the emitter-followers. For a tank with a *Q* of less than 10, this circuit achieves a tuning range of over 20% of the central frequency. The inductor is often a planar spiral layout of thin metal sitting on a lightly conductive substrate. The series resistive loss in the inductor and the field-absorbing loss in the substrate dominate the *Q* of the tank.

A differential version of the negative resistance oscillators is shown in Fig. 21. During operation, transistors Q_1 and Q_2 alternatively turn on and off. The inductor series resonates with the capacitor and with the capacitive input impedance of the two transistors. They present a negative real input impedance when they are on; however, they alternatively turn off, and the real part of the input impedance goes from negative to positive. This simple arrangement provides differential outputs that are useful in several applications in integrated circuit design.

A high-speed, two-stage ring oscillator is depicted in Fig. 22. The buffers consist of slow and fast amplifiers connected in parallel and sitting on top of a differential amplifier. The control voltage allows us to interpolate between slow and fast, by splitting the amount of current available at the current source. The differential amplifier has emitter degeneration resistors to linearize the current partitioning as a function of the differential voltage. Two emitter-
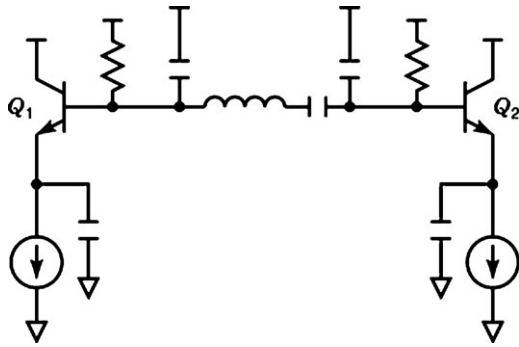
Figure 21. Differential version of negative resistance oscillator.

Figure 23. Crystal oscillator based on Darlington pair used in negative resistance circuit.

followers buffer the outputs between stages and improve jitter by improving the voltage transition time. Both the control and the input/output signals are fully differential, resulting in a circuit that is very tolerant to common mode disturbances. Fully differential oscillators do not depend on reference voltage generators or intrinsic device voltage thresholds to set their operating points. Furthermore, they give us complementary outputs, at twice the differential voltage swing compared to single-ended implementations.

The crystal oscillator with buffered output in Fig. 23 uses two transistors, connected as emitter-followers, in a Darlington arrangement. The input bias current is small, and the resistive loading on the crystal is light. Capacitors C_1 and C_2 connected across the Darlington pair make the
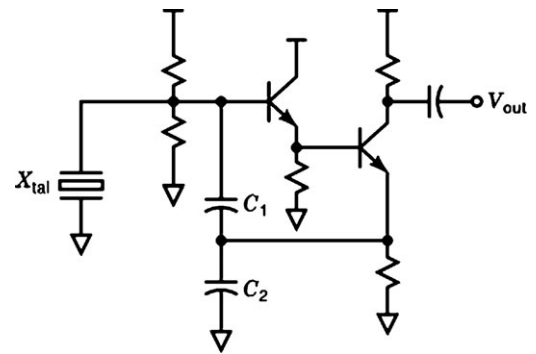
input impedance have a negative real part. This arrangement can therefore be viewed as a negative resistance or one-port oscillator. The oscillation amplitude will be limited by the voltage increase at the emitter of transistor Q_2, which debiases the transistor and limits the maximum current flowing through it. However, the amplitude at the base of transistor Q_1 should not be so large that it saturates it. The output is taken at the collector of transistor Q_2, and the load is elegantly isolated from the core of the oscillator.
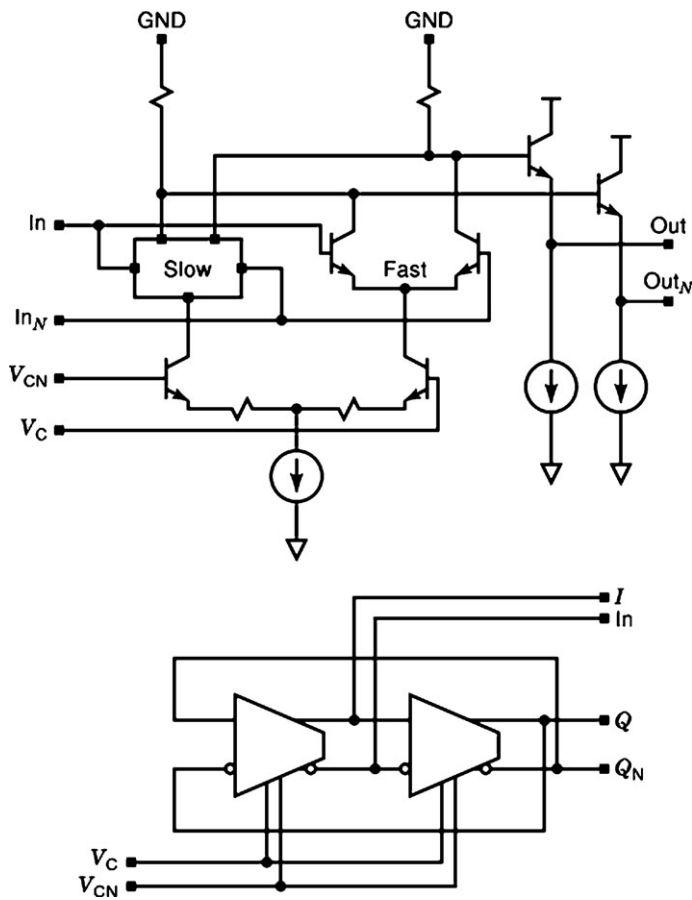

Figure 22. High-speed, two-stage ring oscillator. The frequency is controlled by interpolating the delay of the buffer stages between fast and slow paths.

SUMMARY AND SUGGESTIONS FOR FUTURE STUDY

The design of variable-frequency oscillators requires knowledge of the main topologies, the limits of frequency selective arrangements, the conditions for reliable oscillation, and the available means of tuning, to name the main variables. This article has tried to organize the types of oscillators into two main groups—sinusoidal and relaxation—and has described how their frequencies are changed. A good understanding of a system requires a model of the system. A sinusoidal oscillator can be modeled in two different ways: using feedback and using negative resistance. Relaxation oscillators operating at high frequency can sometimes be modeled in the same way, but in general they are described by their states and their time constants. Simple equivalent circuits and equations for the resonators were presented, attempting to highlight the most intuitive representations.

The variety of oscillators in existence offers many choices, but it also emphasizes the fact that there are unexplored combinations. Particularly because so much of society is influenced by the advances in electronic engineering, and especially integrated circuit engineering, the design of smaller, faster, and cheaper circuits is a very important activity. Variable-frequency oscillators of improved quality are needed today in telecommunications, data transmission, and instrumentation. The components available to design oscillators are constantly undergoing change, most particularly in integrated circuits.

BIBLIOGRAPHY

1. A. P. French *Vibrations and Waves*, New York: Norton, 1971.

2. J. Williams (ed.) *Analog Circuit Design: Art, Science and Personalities*, Stoneham, MA: Butterworth-Heinemann, 1991.

3. The American Radio Relay League, *The ARRL Handbook for Radio Amateurs*, Newington, CT: American Radio Relay League, 1995.

4. J. J. DeFrance *Communications Electronics Circuits*, 2nd ed., Corte Madera, CA: Rinehart Press, 1972.

5. L. E. Larson (ed.) *RF and Microwave Circuit Design for Wireless Communications*, Norwood, MA: Artech House, 1996.

6. J. Millman *Microelectronics: Digital and Analog Circuits and Systems*, New York: McGraw-Hill, 1979.

7. G. Gonzalez *Microwave Transistor Amplifiers*, Englewood Cliffs, NJ: Prentice-Hall, 1984.

8. G. D. Vendelin *Design of Amplifiers and Oscillators by the S-Parameter Method*, New York: Wiley, 1982.

9. M. J. Howes D. V. Morgan (eds.) *Microwave Devices*, New York: Wiley, 1976.

10. R. Meyer Advanced Integrated Circuits for Communications, Univ. California, Berkeley, Course ECE242 Notes, 1994.

11. B. Razavi *RF Microelectronics*, Upper Saddle River, NJ: Prentice-Hall, 1998.

12. U. L. Rohde J. C. Whitaker T. T. Bucher *Communications Receivers: Principles and Design*, New York: McGraw-Hill, 1996.

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