OSCILLATORS

5.12 Introduction to oscillators

Within nearly every electronic instrument it is essential to have an oscillator or waveform generator of some sort. Apart from the obvious case of signal generators, function generators, and pulse generators themselves, a source of regular oscillations is necessary in any cyclical measuring instrument, in any instrument that initiates measurements or processes, and in any instrument whose function involves periodic states or periodic waveforms. That includes just about everything. For example, oscillators or waveform generators are used in digital multimeters, oscilloscopes, radiofrequency receivers, computers, every computer peripheral (tape, disk, printer, alphanumeric terminal), nearly every digital instrument (counters, timers, calculators, and anything with a "multiplexed display"), and a host of other devices too numerous to mention. A device without an oscillator either doesn't do anything or expects to be driven by something else (which probably contains an oscillator). It is not an exaggeration to say that an oscillator of some sort is as essential an ingredient in electronics as a regulated supply of dc power.

Depending on the application, an oscillator may be used simply as a source of regularly spaced pulses (e.g., a "clock" for a digital system), or demands may be made on its stability and accuracy (e.g., the time base for a frequency counter), its adjustability (e.g., the local oscillator in a transmitter or receiver), or its ability to produce accurate waveforms (e.g., the horizontal-sweep ramp generator in an oscilloscope).

In the following sections we will treat briefly the most popular oscillators, from the simple *RC* relaxation oscillators to the stable quartz-crystal oscillators. Our aim is not to survey everything in exhaustive detail, but simply to make you acquainted with what is available and what sorts of oscillators are suitable in various situations.

5.13 Relaxation oscillators

A very simple kind of oscillator can be made by charging a capacitor through a

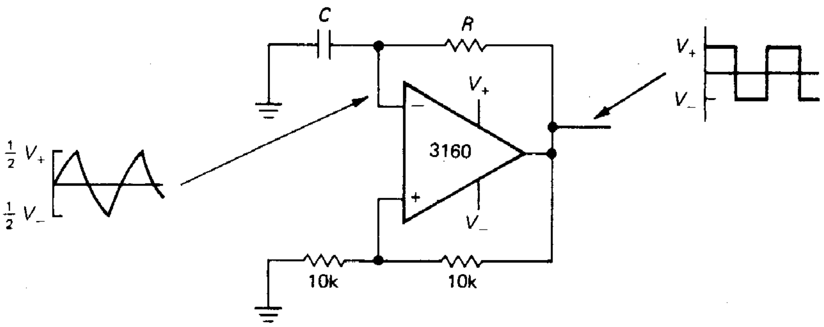


Figure 5.29. Op-amp relaxation oscillator.

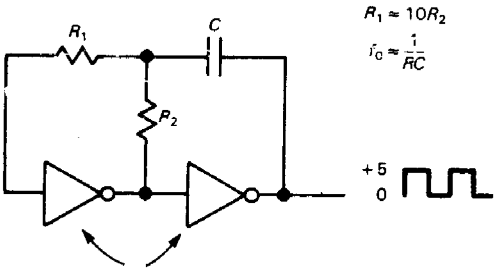
resistor (or a current source), then discharging it rapidly when the voltage reaches some threshold, beginning the cycle anew. Alternatively, the external circuit may be arranged to reverse the polarity of the charging current when the threshold is reached, thus generating a triangle wave rather than a sawtooth. Oscillators based on this principle are known as relaxation oscillators. They are inexpensive and simple, and with careful design they can be made quite stable in frequency.

In the past, negative-resistance devices such as unijunction transistors and neon bulbs were used to make relaxation oscillators, but current practice favors op-amps or special timer ICs. Figure 5.29 shows a classic *RC* relaxation oscillator. The operation is simple: Assume that when power is first applied, the op-amp output goes to positive saturation (it's actually a toss-up which way it will go, but it doesn't matter). The capacitor begins charging up toward V_+, with time constant *RC*. When it reaches one-half the supply voltage, the op-amp switches into negative saturation (it's a Schmitt trigger), and the capacitor begins discharging toward V_- with the same time constant. The cycle repeats indefinitely, with period 2.2*RC*, independent of supply voltage. A CMOS output-stage op-amp (see Sections 4.11 and 4.22) was chosen because its outputs saturate cleanly at the supply voltages. The bipolar LM10 also swings rail-to-rail and, unlike CMOS op-amps, allows operation at a full ±15 volts; however, it has a much lower f_T (0.1MHz).

EXERCISE 5.7

Show that the period is as stated.

By using current sources to charge the capacitor, a good triangle wave can be generated. A clever circuit using that principle was shown in Section 4.29.



"CMOS inverters"
(each is $\frac{1}{6}$ of a 74HC04;
powered from +5V)

Figure 5.30

Sometimes you need an oscillator with very low noise content (also called "low sideband noise"). The simple circuit of Figure 5.30 is good in this respect. It uses a pair of CMOS inverters (a form of digital logic we'll use extensively in Chapters 8–11) connected together to form an *RC* relaxation oscillator with square wave output. Actual measurements

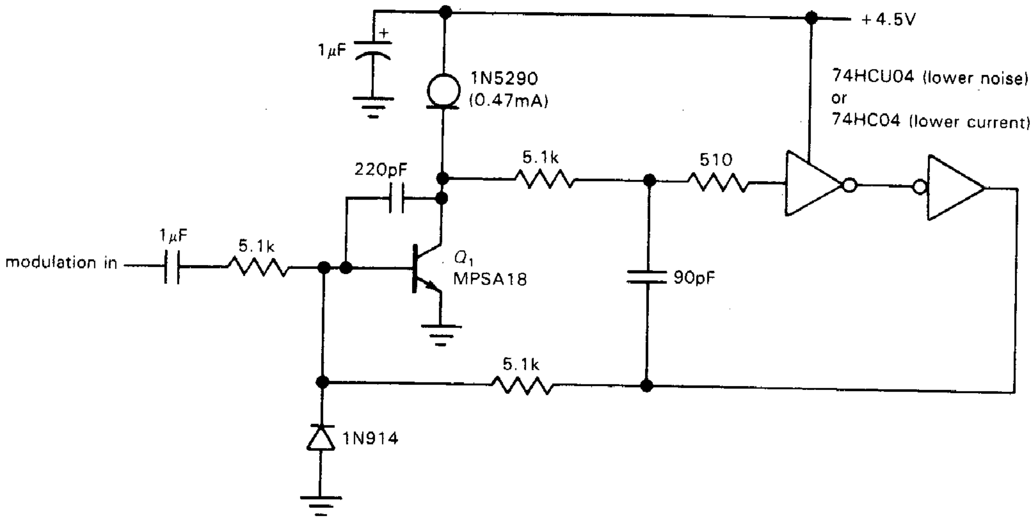


Figure 5.31. Low-noise oscillator.

on this circuit running at 100kHz show close-in sideband noise power density (power per square root hertz, measured 100Hz from the oscillator frequency), down at least 85dB relative to the carrier. You sometimes see a similar circuit, but with R_2 and C interchanged. Although it still oscillates fine, it is extremely noisy by comparison.

The circuit of Figure 5.31 has even lower noise and furthermore lets you modulate the output frequency via an external current applied to the base of Q_1. In this circuit Q_1 operates as an integrator, generating an asymmetrical triangle waveform at its collector. The inverters operate as a noninverting comparator, alternating the polarity of the base drive each half cycle. This circuit has close-in noise density of $-90\text{dBc}/\sqrt{\text{Hz}}$ measured 100Hz from the 150kHz carrier, and $-100\text{dBc}/\sqrt{\text{Hz}}$ measured at an offset of 300Hz. Although these circuits excel in low sideband noise, the oscillation frequency has more supply-voltage sensitivity than other oscillators discussed in this chapter.

5.14 The classic timer chip: the 555

The next level of sophistication involves the use of timer or waveform-generator ICs as relaxation oscillators. The most popular chip around is the 555 (and its successors). It is also a misunderstood chip, and we intend to set the record straight with the equivalent circuit shown in Figure 5.32. Some of the symbols belong to the digital world (Chapter 8 and following), so you won't become a 555 expert for a while yet. But the operation is simple enough: The output goes HIGH (near V_{CC}) when the 555 receives a TRIGGER' input, and it stays there until the THRESHOLD input is driven, at which time the output goes LOW (near ground) and the DISCHARGE transistor is turned on. The TRIGGER' input is activated by an input level below $\frac{1}{3}V_{CC}$, and the THRESHOLD is activated by an input level above $\frac{2}{3}V_{CC}$.

The easiest way to understand the workings of the 555 is to look at an example (Fig. 5.33). When power is applied, the capacitor is discharged; so the 555 is triggered, causing the output to go HIGH, the discharge transistor Q_1 to turn

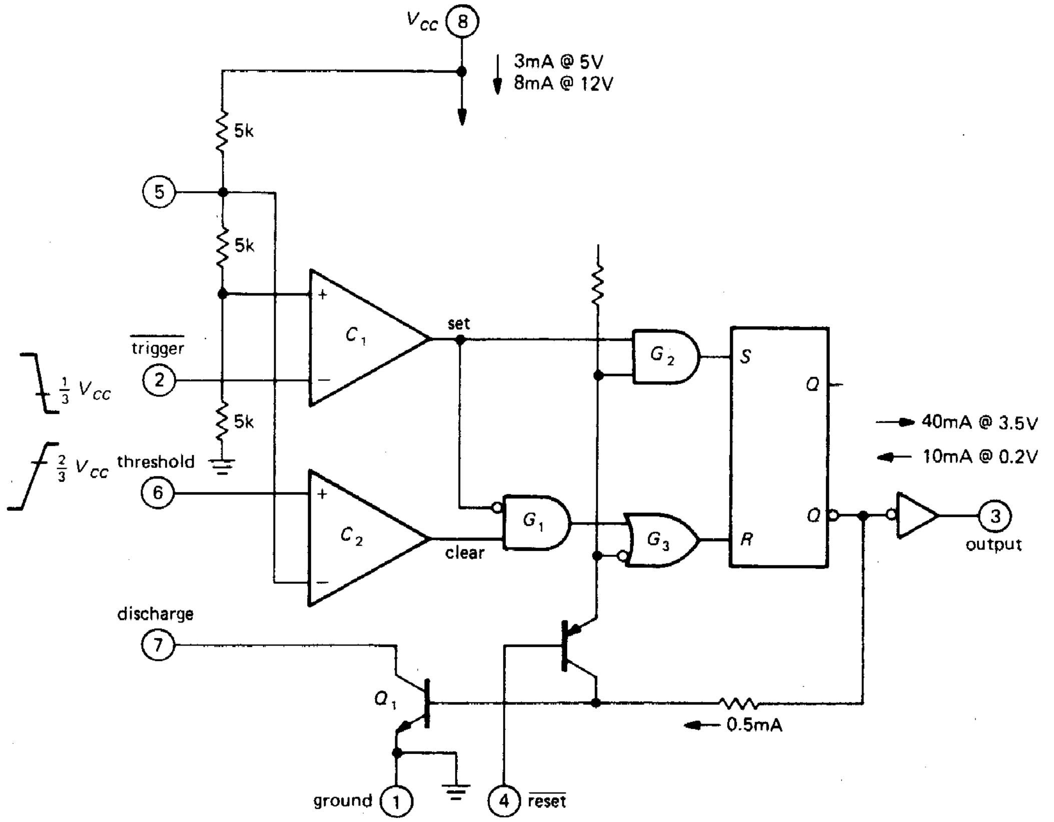


Figure 5.32. Simplified 555 schematic.

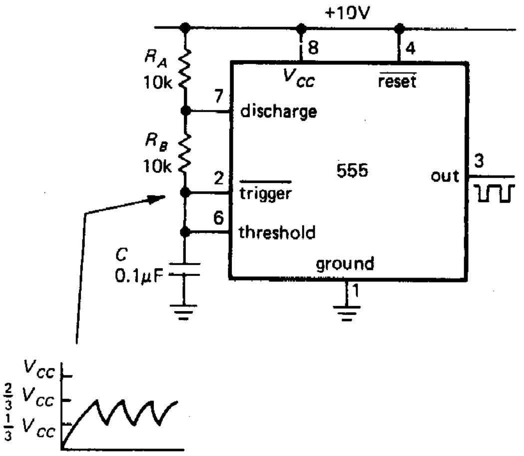


Figure 5.33. The 555 connected as an oscillator.

off, and the capacitor to begin charging toward 10 volts through $R_A + R_B$. When it has reached $\frac{2}{3}V_{CC}$, the THRESHOLD input is triggered, causing the output to go LOW and Q_1 to turn on, discharging C toward ground through R_B. Operation is now cyclic, with C's voltage going between $\frac{1}{3}V_{CC}$ and $\frac{2}{3}V_{CC}$, with period $T = 0.693(R_A + 2R_B)C$. The output you generally use is the square wave at the output.

EXERCISE 5.8

Show that the period is as advertised, independent of supply voltage.

The 555 makes a respectable oscillator, with stability approaching 1%. It can run from a single positive supply of 4.5 to 16 volts, maintaining good frequency stability with supply voltage variations because the thresholds track the supply fluctuations. The 555 can also be used to generate single pulses of arbitrary width, as well as a bunch of other things. It is really a small kit, containing comparators, gates, and flip-flops. It has become a game in the electronics industry to try to think of new uses for the 555. Suffice it to say that many succeed at this new form of entertainment.

A caution about the 555: The 555, along with some other timer chips, generates a big (≈150mA) supply-current glitch during each output transition. Be sure to use a hefty bypass capacitor near the chip. Even so, the 555 may have a tendency to generate double output transitions.

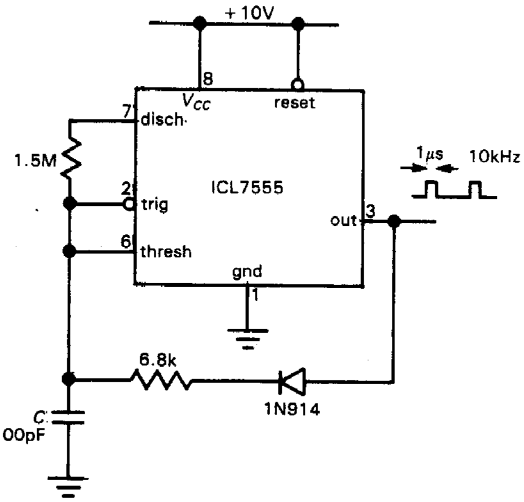


Figure 5.34. Low-duty-cycle oscillator.

CMOS 555s

Some of the less desirable properties of the 555 (high supply current, high trigger current, double output transitions, and inability to run with very low supply voltage) have been remedied in a collection of CMOS successors. You can recognize these by the telltale "555" somewhere in the part number. Table 5.3 lists most of these that we could find, along with their important specifications. Note particularly the ability to operate at very low supply voltage (down to 1V!) and the generally low supply current. These chips also can run at higher frequency than the original 555. The CMOS output stages give rail-to-rail swing, at least at low load currents (but note that these chips don't have the output-current muscle of the standard 555). All chips listed are CMOS except for the original 555 and the XR-L555. The latter is intended as a bipolar low-power 555 and reveals its pedigree by the hefty output sourcing capability and good tempco.

The 555 oscillator of Figure 5.33 generates a rectangular-wave output whose duty cycle (fraction of time the output is HIGH) is always greater than 50%. That is because the timing capacitor is charged through the series pair $R_A + R_B$, but discharged (more rapidly) through R_B alone. Figure 5.34 shows how to trick the 555 into giving you low duty-cycle positive pulses. The diode/resistor combination *charges* timing capacitor rapidly via the output, with slower discharge via the internal discharge transistor. You can only play this trick with a CMOS 555, because you need the full positive output swing.

By using a current source to charge the timing capacitor, you can make a ramp (or "sawtooth-wave") generator. Figure 5.35 shows how, using a simple *pnp* current source. The ramp charges to $\frac{2}{3}V_{CC}$, then discharges rapidly (through the 555's *npn* discharge transistor, pin 7) to $\frac{1}{3}V_{CC}$, beginning the ramp cycle anew. Note that the ramp waveform appears on the capacitor terminal and must be buffered with an op-amp since it is at high impedance. In this circuit you could simplify things somewhat by using a JFET "current-regulator diode" (Section 3.06) in place of the *pnp* current source; however, the performance (ramp linearity) would be slightly degraded, because a JFET operating at I_{DSS} is not as good a current source as the bipolar transistor circuit.

Figure 5.36 shows a simple way to

TABLE 5.3. 555-TYPE OSCILLATORS

Type	Mfg[a]	Qty per package	Supply voltage		Supply curr per osc ($V_S = 5V$)		Trig, thresh current		Max freq ($V_S = 5V$)		Tempco typ (ppm/°C)	V_{sat}, typ				Rail to rail?[b]	I_{out}, max (V_S=5V, V_O=2.5V)	
		1 2 4	min (V)	max (V)	typ (µA)	max (µA)	typ (nA)	max (nA)	min (MHz)	typ (MHz)		V_{OH} (V)	@ I_{src} (mA)	V_{OL} (V)	@ I_{snk} (mA)		source (mA)	sink (mA)
555	SN+	• • –	4.5	18	3000	5000	100	500	–	0.5	30	1.4	2	0.1	10	–	200	200
ICL7555	IL	• • –	2	18	60	300	–	10	–	1	150	1	2	0.5	10	•	4	25
TLC551	TI	• • –	1	18	170	–	0.01	–	–	2.1[c]	–	1	2	0.2	10	•	–	–
TLC555	TI	• • –	2	18	170	–	0.01	–	–	2.1	–	1	2	0.2	10	•	–	–
LMC555	NS	• – –	1.5	15	100	250	0.01	–	–	3	75	0.3	2	0.3	10	•	–	–
ALD555-1	AL	• – –	1	12	100	180	0.001	0.2	1.4	2	300	0.4	2	0.2	10	•	3	100
ALD1504	AL	• • –	1	12	50	90	0.01	0.4	1.5	2.5	300	0.4	2	0.2	10	•	10	100
ALD4503	AL	– – •	1	12	35	70	0.01	0.4	–	2	300	0.4	2	0.2	10	•	3	100
XR-L555M	XR	• • –	2.7	15	150	300	500	–	–	–	30	1.7	10	0.3	2	–	100	–

(a) see footnotes to Table 4.1. (b) signifies that the output stage can swing to both rails. (c) at V_S=1.2V.

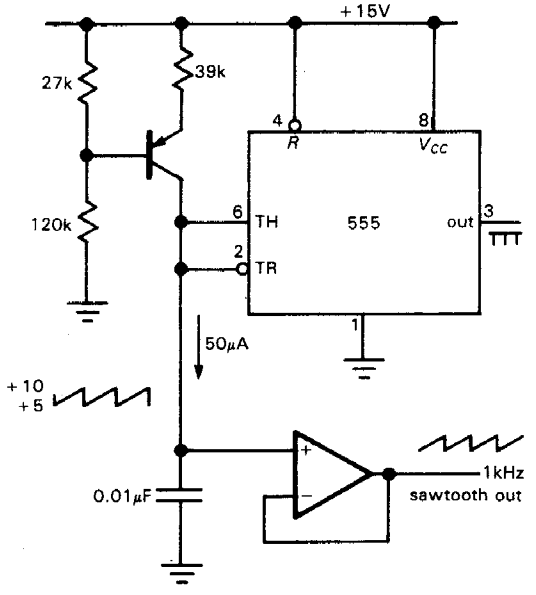


Figure 5.35. Sawtooth oscillator.

generate a *triangle* wave with a CMOS 555. Here we wired a pair of JFET current regulators in series to generate a bidirectional current regulator (each current regulator behaves like a normal diode in the reverse direction, owing to gate-drain conduction). The rail-to-rail output swing thus generates a constant current, of alternating polarity, producing a triangle waveform (going between the usual $\frac{1}{2}V_{CC}$ and $\frac{2}{3}V_{CC}$) at the capacitor. As before, you have to buffer the high-impedance waveform with an op-amp. Note that you must use a *CMOS* 555, particularly when operating the circuit from +5 volts, since the circuit depends on a full rail-to-rail output swing. For example, the HIGH output of a bipolar 555 is typically 2 diode drops below the positive rail (*npn* Darlington follower), or +3.8 volts with a 5 volt supply; this leaves only 0.5 volt across the series pair of current regulators at the top of the waveform, obviously insufficient to turn on the current regulator (approximately 1V) and the series JFET diode (0.6V).

EXERCISE 5.9

Demonstrate that you understand the circuits of Figures 5.35 and 5.36 by calculating the frequency of oscillation in each case.

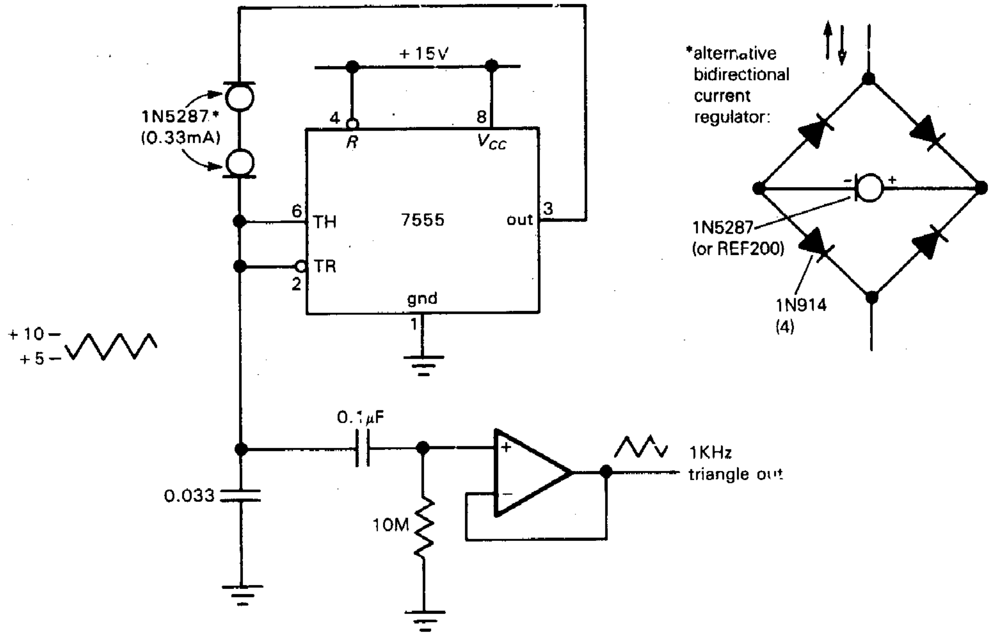


Figure 5.36. Triangle generator.

There are some other interesting timer chips available. The 322 timer from National includes its own internal precision voltage reference for determining the threshold. That makes it an excellent choice for generating a frequency proportional to an externally supplied current, as, for example, from a photodiode. Another class of timers uses a relaxation oscillator followed by a digital counter, in order to generate long delay times without resorting to large resistor and capacitor values. Examples of this are the 74HC4060, the Exar 2243, and the Intersil ICM7242 (also made by Maxim). The latter is CMOS, runs on a fraction of a milliamp, and generates an output pulse every 128 oscillator cycles. These timers (and their near relatives) are great for generating delays from a few seconds to a few minutes.

☐ 5.17 Wien bridge and *LC* oscillators

When a low-distortion sine wave is required, none of the preceding methods is generally adequate. Although wide-range function generators do use the technique of "corrupting" a triangle wave with diode clamps, the resulting distortion can rarely be reduced below 1%. By comparison, most hi-fi audiophiles insist on distortion levels below 0.1% for their amplifiers. To test such low-distortion audio components, pure sine-wave signal sources with residual distortion less than 0.05% or so are required.

At low to moderate frequencies the Wien bridge oscillator (Fig. 5.42) is a good source of low-distortion sinusoidal signals. The idea is to make a feedback amplifier with 180° phase shift at the desired output frequency, then adjust the loop gain so that a self-sustaining oscillation just barely takes place. For equal-value Rs and Cs as shown, the voltage gain from the noninverting input to op-amp output should be exactly +3.00. With less gain the oscillation will cease, and with more gain the output will saturate. The distortion is low if the amplitude of oscillation remains within the linear region of the amplifier, i.e., it must not be allowed to go into a full-swing oscillation. Without some trick to control the gain, that is exactly what will happen, with the amplifier's output increasing until the effective gain is reduced to 3.0 because of saturation. The tricks involve some sort of long-time-constant gain-setting feedback, as you will see.

In the first circuit, an incandescent lamp is used as a variable-resistance feedback element. As the output level rises, the lamp heats slightly, reducing the noninverting gain. The circuit shown has less

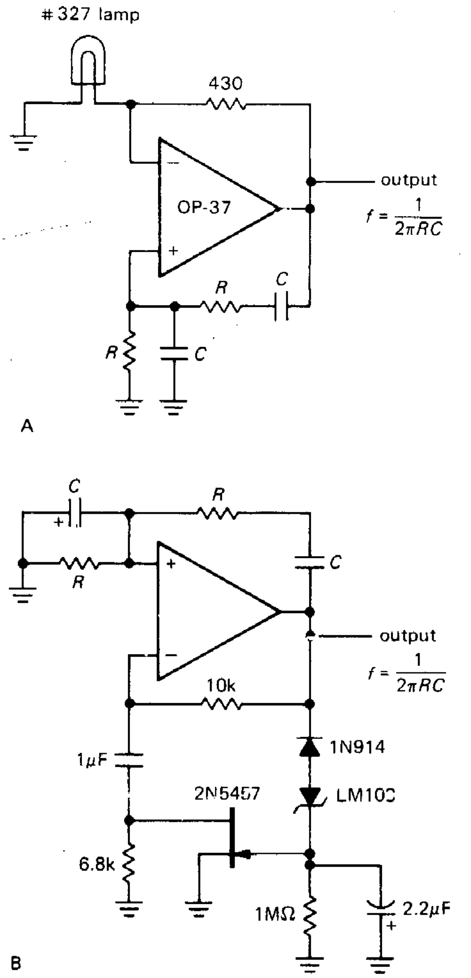


Figure 5.42. Wien-bridge low-distortion oscillators.

than 0.003% harmonic distortion for audiofrequencies above 1kHz; see LTC App. Note 5(12/84) for more details. In the second circuit, an amplitude discriminator consisting of the diodes and *RC* adjusts the ac gain by varying the resistance of the FET, which behaves like a voltage-variable resistance for small applied voltages (see Section 3.10). Note the long time constant used (2s); this is essential to avoid distortion, since fast feedback will distort the wave by attempting to control the amplitude within the time of one cycle.

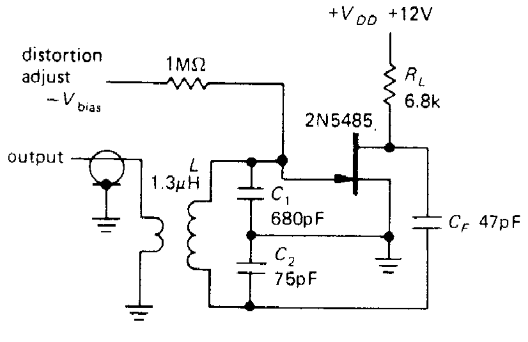
☐ 5.18 *LC* oscillators

At high frequencies the favorite method of sine-wave generation is an *LC*-controlled oscillator, in which a tuned *LC* is connected in an amplifier-like circuit to provide gain at its resonant frequency. Overall positive feedback is then used to cause a sustained oscillation to build up at the *LC*'s resonant frequency; such circuits are self-starting.

Figure 5.43 shows two popular configurations. The first circuit is the trusty Colpitts oscillator, a parallel tuned *LC* at the input, with positive feedback from the output. For this circuit it is claimed that its distortion is less than −60dB. The second circuit is a Hartley oscillator, built with an *npn* transistor. The variable capacitor is for frequency adjustment. Both circuits use *link coupling*, just a few turns of wire acting as a step-down transformer.

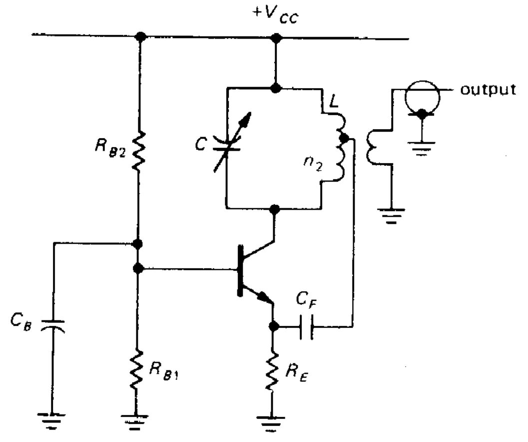
LC oscillators can be made *electrically* tunable over a modest range of frequency. The trick is to use a voltage-variable capacitor ("varactor") in the frequency-determining *LC* circuit. The physics of diode junctions provides the solution, in the form of a simple reverse-biased diode: The capacitance of a *pn* junction decreases with increasing reverse voltage (see Fig. 13.3). Although any diode acts as a varactor, you can get special varactor diodes designed for the purpose; Figure 5.44 shows some representative types. Figure 5.45 shows a simple JFET Colpitts oscillator (with feedback from the source) with ±1% tunability. In this circuit the tuning range has been made deliberately small, in order to achieve good stability, by using a relatively large fixed capacitor (100pF) shunted by a small tunable capacitor (maximum value of 15pF). Note the large biasing resistor (so the diode bias circuit doesn't load the oscillation) and the dc blocking capacitor. See also Section 13.11.

Varactors typically provide a maximum capacitance of a few picofarads to a few



20MHz low-distortion Colpitts oscillator

A



B Hartley LC oscillator

Figure 5.43

hundred picofarads, with a tuning range of about 3:1 (although there are wide range varactors with ratios as high as 15:1). Since the resonant frequency of an LC circuit is inversely proportional to the square root of capacitance, it is possible to achieve tuning ranges of up to 4:1 in frequency, though more typically you're talking about a tuning range of ±25% or so.

In varactor-tuned circuits the oscillation itself (as well as the externally applied dc tuning bias) appears across the varactor, causing its capacitance to vary at the signal frequency. This produces oscillator waveform distortion, and, more important, it causes the oscillator frequency to depend somewhat on the amplitude of oscillation. In order to minimize these effects, you should limit the amplitude of the oscillation (amplify in following stages, if you need more output); also, it's best to keep the dc varactor bias voltage above a volt or so, in order to make the oscillating voltage small by comparison.

Electrically tunable oscillators are used extensively to generate frequency modulation, as well as in radiofrequency phase-locked loops. We will treat these subjects in Chapters 9 and 13.

For historical reasons we should mention a close cousin of the LC oscillator, namely the tuning-fork oscillator. It used the high-Q oscillations of a tuning fork as the frequency-determining element of an oscillator, and it found use in low-frequency standards (stability of a few parts per million, if run in a constant-temperature oven) as well as wristwatches. These objects have been superseded by quartz oscillators, which are discussed in the next section.

☐ *Parasitic oscillations*

Suppose you have just made a nice amplifier and are testing it out with a sine-wave input. You switch the input function generator to a square wave, but the output remains a sine wave! You don't have an amplifier; you've got trouble.

Parasitic oscillations aren't normally as blatant as this. They are normally observed as fuzziness on part of a waveform, erratic current-source operation, unexplained op-amp offsets, or circuits that behave normally with the oscilloscope probe applied, but go wild when the scope isn't looking. These are bizarre manifestations of untamed high-frequency parasitic oscillations caused by unintended Hartley or Colpitts oscillators employing lead inductance and interelectrode capacitances.

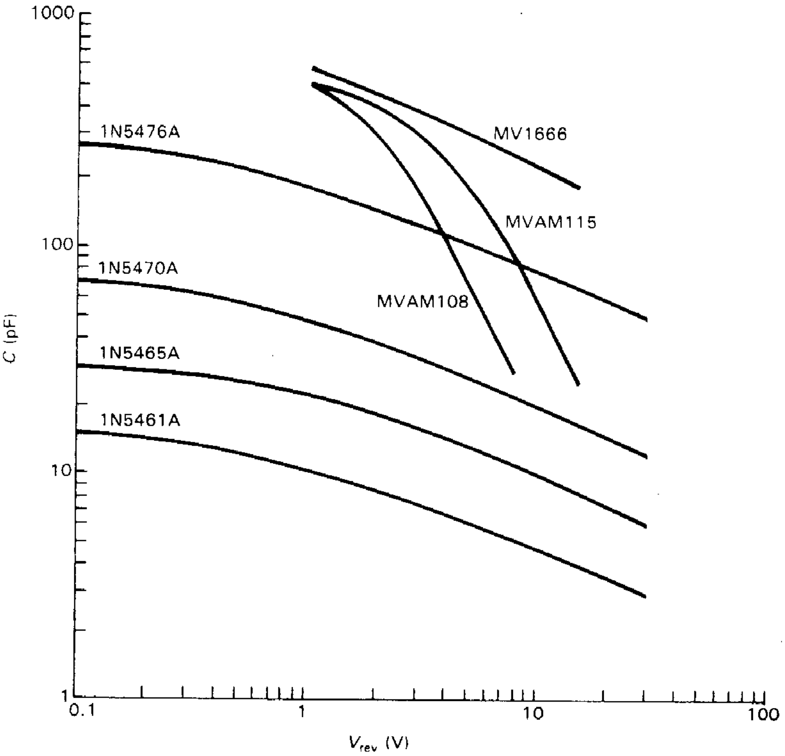


Figure 5.44. Varactor tuning diodes.

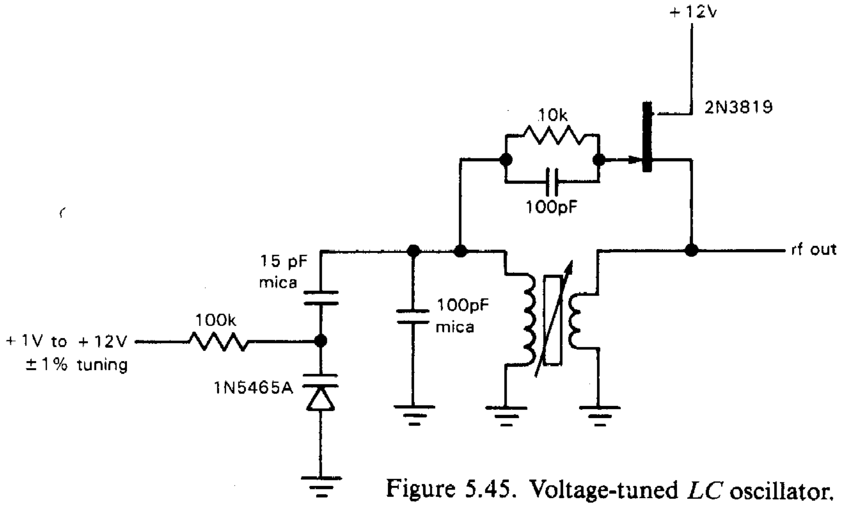


Figure 5.45. Voltage-tuned *LC* oscillator.

The circuit in Figure 5.46 shows an oscillating current source born in an electronics lab course where a VOM was used to measure the output compliance of a standard transistor current source. The current seemed to vary excessively (5% to 10%) with load voltage variations within its expected compliance range, a symptom that could be "cured" by sticking a finger on the collector lead! The collector-base

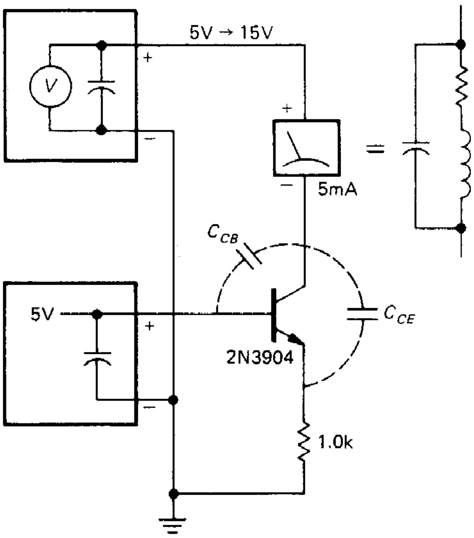


Figure 5.46. Parasitic oscillation example.

capacitance of the transistor and the meter capacitance resonated with the meter inductance in a classic Hartley oscillator circuit, with feedback provided by collector-emitter capacitance. Adding a small base resistor suppressed the oscillation by reducing the high-frequency common-base gain. This is one trick that often helps.