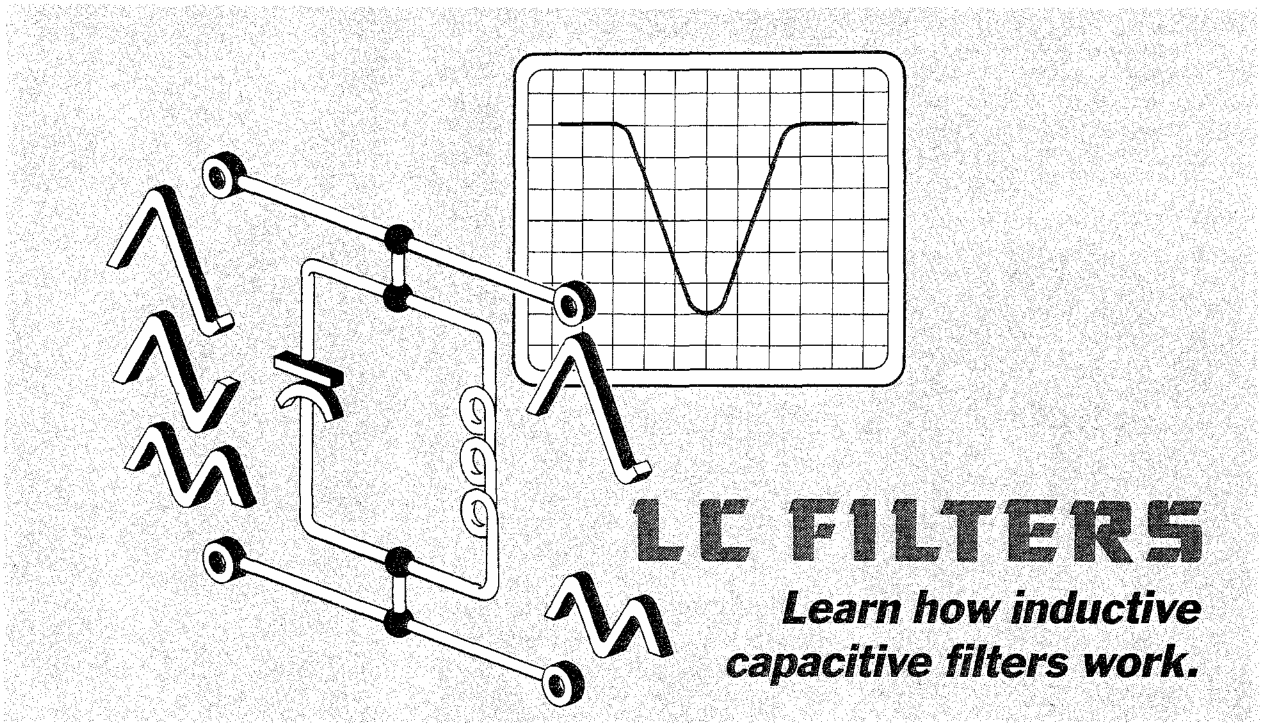

LC FILTERS

Learn how inductive capacitive filters work.

RAY MARSTON

THE PRIMARY APPLICATION FOR RESonant inductive capacitive (LC) filters these days are in high-frequency circuits. These filters, like resistive capacitive (RC) filters can easily be designed to perform low-pass, high-pass, bandpass, or notch filtering, but they have the additional benefit of offering at least 12 dB per octave of rolloff, compared to the 6 dB per octave of RC filters, which means sharper cutoff characteristics at all operating frequencies.

The series- and the parallel-resonant LC filters are the two "watershed" LC designs from which all others are derived. Figure 1-*a* shows a circuit for a series-resonant filter, and Fig. 1-*b* shows its simplified equivalent circuit. The R represents the resistance of the coil.

Series-resonant filter

The fundamental response of the series filter is that capacitive reactance C decreases with increased frequency, while inductive reactance decreases. The inverse relationship also holds. The filter's input impedance is equal to the difference between these two reactances, plus the value of resistor R.

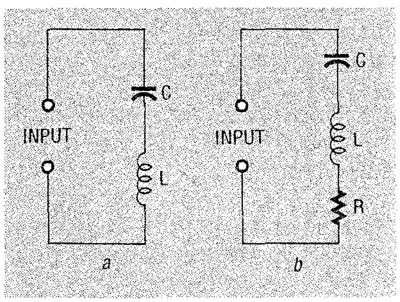

FIG. 1—LC SERIES-RESONANT filters: simplified schematic, *a*, and equivalent circuit, *b*.

At some specific frequency, the reactances of C and L could be 10 kilohms and 1 kilohm, respectively. Therefore the filter's input impedance (ignoring the value of R) will be 9 kilohms at that frequency. Many other similar examples can be given.

The key point to be made here is that at resonant frequency, f_c, the reactances of C and L will be equal (but 90° out of phase), and the filter input impedance will equal the value of R, as indicated by the dotted line at the bottom of the impedance vs. frequency characteristic curve Fig. 2-*a*. For example, if this occurs when the reactances of C and L are both 1000 ohms, and R equals 10 ohms, the input impedance would be 10 ohms, and the entire signal voltage would be generated across R.

The signal currents through effective resistance R flow through C and L, which both have reactances 100 times greater than the value of R in ohms. Consequently, the signal

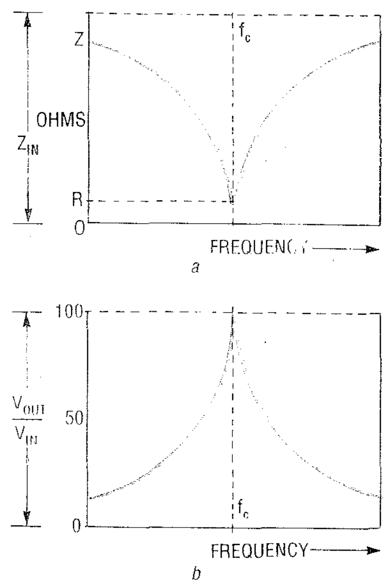

FIG. 2—LC SERIES-RESONANT FILTER: Plot of input impedance vs. frequency at resonance, *a*, plot of voltage output vs. frequency at resonance taken across L or C, *b*.

voltage generated across C and L is 100 times greater than the actual input signal voltage, as shown in Fig. 2-*b*, the curve of voltage vs. frequency. This voltage magnification, indicated by the sharp peak, is known as the circuit's Q.

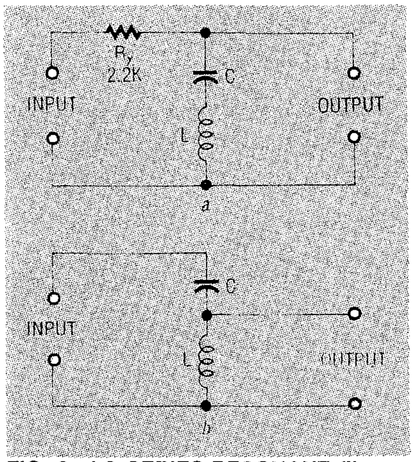

FIG. 3—LC SERIES-RESONANT filters: notch rejector, *a*, and notch acceptor, *b*.

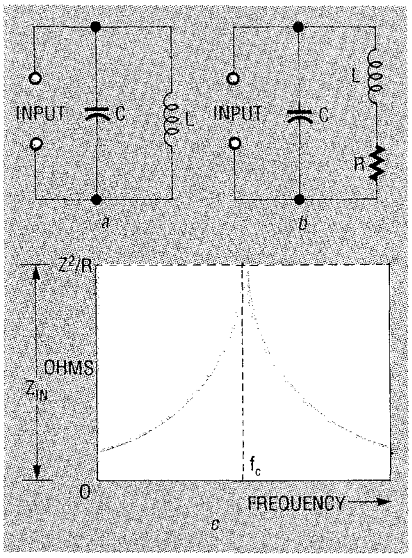

FIG. 4—LC PARALLEL-RESONANT filters: simple schematic, *a*, equivalent circuit, *b*, and plot of input impedance vs. frequency, *c*.

Notice in Fig. 2-*b* that the inductive and capacitive voltages are 90° out of phase, and the voltage generated across the series LC combination is effectively zero. The impedence of the filter at f_c is known as the filter's *characteristic impedance*, Z_O, and it equals $\sqrt{L/C}$.

Figure 3 shows two ways to make practical use of a series-resonant LC filter: In Fig. 3-*a*, 2.2 kilohm resistor R_x and the filter act together as a frequency-selective attenuator that gives high attenuation at the resonant frequency f_c, and lower attenuation above or below that resonant frequency. (The filter is a *notch rejector*.)

In Fig. 3-*b*, the input signal is applied directly to the filter, and the output is taken across the inductor L. This filter circuit acts as a *notch acceptor* that provides high gain at resonant frequency f_c and low gain above or below that frequency.

Table 1 lists the principal formulas that can be applied to both series- and parallel-resonant LC circuits.

Parallel-resonant filters

Figure 4-*a* shows the schematic for a parallel-resonant filter, and Fig. 4-*b* shows its equivalent circuit. The inductor's resistance is represented by R. In this filter, capacitive reactance decreases with increasing frequency, and inductive reactance increases with increasing frequency. The reciprocal relationship also holds.

Each component draws a signal current that is proportional to its reactance, but the two currents are 90° out-of-phase, so the total signal current is equal to the difference between the L and C currents. At resonance, L and C are equal so the total current falls nearly to zero.

As a result, the filter acts as a near-infinite impedance. In practical filters, the presence of equivalent resistance R modifies the response by reducing the impedance at the resonant frequency f_c, Z_c, to Z_o^2/R. For example, if Z_o equals 1 kilohm and R equals 10 ohms, the value of Z_c will be 100 kilohms.

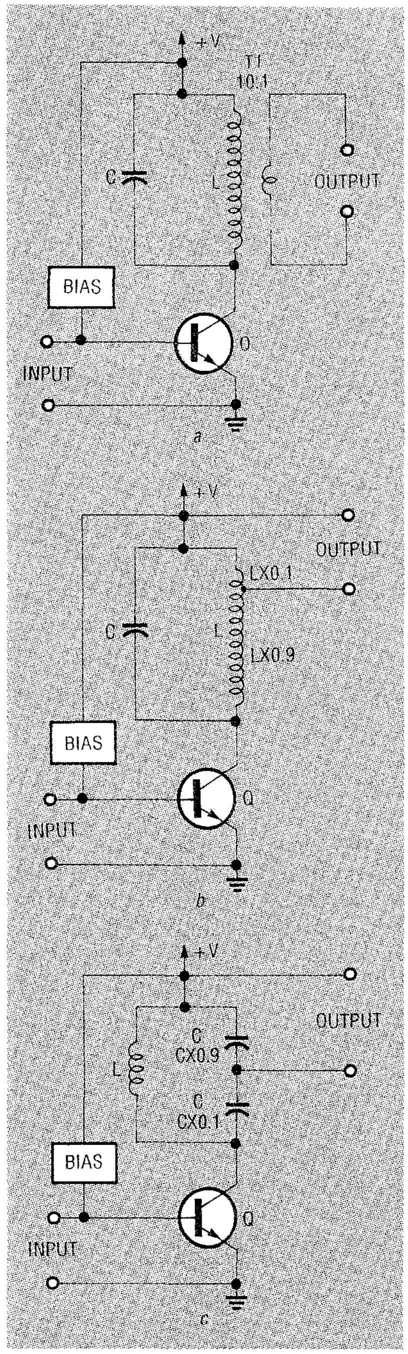

FIG. 5—LC TUNED AMPLIFIERS with low-impedance outputs: transformer coupling, *a*, auto-transformer coupling, *b*, and capacitive-divider coupling, *c*.

TABLE 1
DESIGN FORMULAS FOR INDUCTIVE-CAPACITIVE FILTERS
Formulas apply to series and parallel LC filters

$$f_c = \frac{1}{2\pi\sqrt{LC}} \text{ hertz} \qquad Z_o = \sqrt{\frac{L}{C}} \text{ ohms}$$

$$L = \frac{Z_o}{2\pi f_c} \text{ henries} \qquad C = \frac{1}{2\pi f_c Z_o} \text{ farads}$$

$$Q = \frac{X_L}{R} = \frac{Z_o}{R}$$

Note : f_c, Z_o, X_L

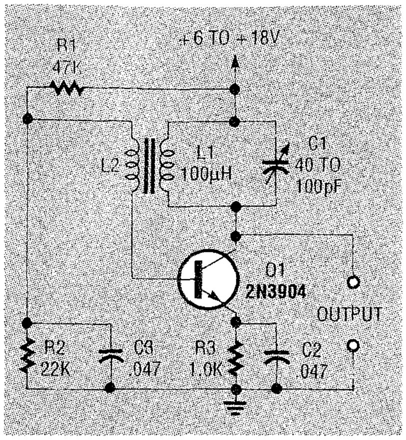

FIG. 6—TUNED-COLLECTOR feedback LC oscillator.

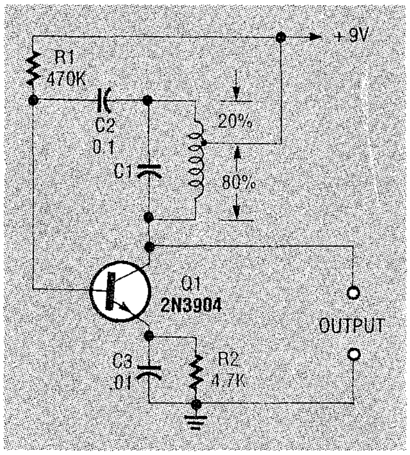

FIG. 7—SIMPLE HARTLEY LC oscillator.

Figure 4-*c* is the filter's frequency response: a plot of input impedance vs. frequency showing how the input impedance peaks at the resonant frequency f_c. All of the formulas in Table 1 apply to the parallel-resonant filter as well.

Output coupling

The two most popular applications for parallel-resonant tuned filters are in narrow frequency band amplifiers and in LC oscillators. In narrow-band amplifiers the filter usually functions as the collector load for common-emitter amplifiers as shown by three simplified schematics in Fig. 5. The filter provides high gain at its resonant frequency and lower gain above and below that frequency.

The drawback to these circuits is the problem of gaining access to the circuit's output signals without loading the tuned circuit and lowering its effective Q. Three ways to overcome this drawback are illustrated in Fig. 5.

One way to obtain output coupling is to consider the primary winding of an RF transformer as the filter's inductive component, and to take the output from the transformer's secondary, as shown in Fig. 5-*a*. This approach provides a fully floating output. If the transformer has a 10:1 turns ratio, the output signal will have an attenuation factor *a* of 10.

In a second method, the coil can be tapped as shown in Fig. 5-*b*, to obtain an output by autotransformer action. In the third method, as shown in Fig. 5-*c*, the required tuning capacitance is obtained from two series-connected capacitors. An output can be obtained across the larger capacitor by capacitive divider action.

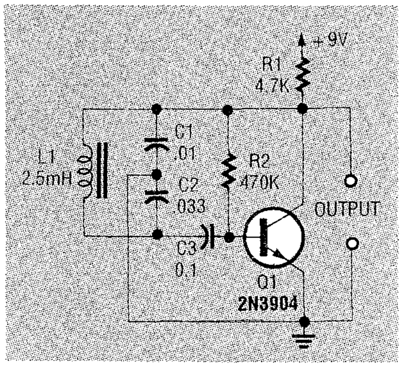

FIG. 8—COLPITTS LC OSCILLATOR produces a 37-kHz output.

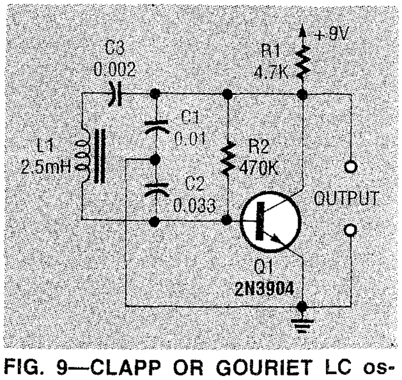

FIG. 9—CLAPP OR GOURIET LC oscillator producese an 80-kHz output.

In these schematics each circuit has arbitrarily been given an attenuation factor *a* of 10. Each has an output impedance of Z_c/a^2. Thus, if Z_c equals 100 kilohms and *a* equals 10, the Z output equals 1 kilohm.

LC oscillators

Figures 6 through 10 illustrate the different schemes for using a parallel-resonant filter as the tuning element in transistorized LC oscillators. The simplest of the LC oscillators is the *tuned-collector feedback* form shown in Fig. 6.

Transistor Q1 is connected as a common-emitter amplifier, L1 and C1 form the tuned collector filter, and L2 provides the collector-to-base feedback. Inductor L2 is inductively coupled to L1, providing transformer action. By adjusting the phase of this feedback signal, the circuit will give zero phase shift at the tuned frequency so that, if the loop gain (determined by T1's turns ratio) is greater than unity, the circuit oscillates. With the component values shown, oscillation frequency can be varied from 1 MHz to 2 MHz by trimmer capacitor C1.

Figure 7 is the schematic for a simple Hartley oscillator. The turns of collector load inductor L1 are tapped at a point 20% down from the top of the coil, and the circuit's positive power supply is connected to this tap point. As a result, L1 acts as an autotransformer so that the signal voltage appearing at the top of L1 is 180° out of phase with the voltage at its low end (nearest Q1's collector.)

The signal voltage at the top of the coil, (which is 180° out of phase with the signal at Q1's collector) is coupled the base of Q1 base by isolating capacitor C2. In this arrangement the circuit oscillates at a center frequency

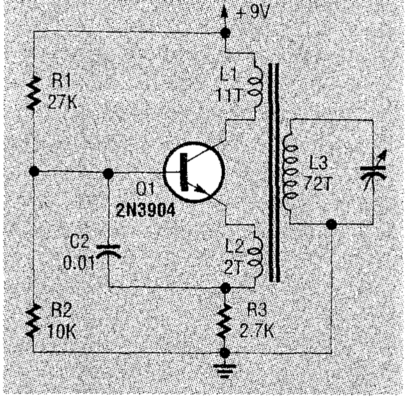

FIG. 10—SIMPLE REINARTZ LC oscillator.

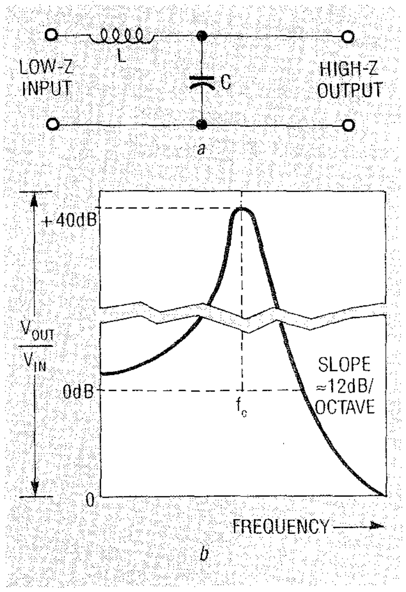

FIG. 11—FALSE L-TYPE LOW-PASS filter: schematic *a*, and frequency response curve.

determined by the values of L and C.

In general, circuit oscillation depends on tapping a common signal at a point in the tuned circuit so that phase-splitting autotransformer response is obtained. This tap point need not be made in the tuning coil; it can be made in the tuning capacitor, as in the Colpitts oscillator shown in schematic Fig. 9. With the component values in that figure, the oscillator will oscillate at about 37 kHz.

In Fig. 8, C1 is in parallel with transistor Q1's output capacitance, and C2 is in parallel with Q1's input capacitance. Consequently, capacitance changes caused by ambient and component temperature changes can shift the oscillation frequency.

This shift can be minimized and good frequency stability can be obtained by selecting values for C1 and C2 that are large with respect to Q1's internal capacitance.

Figure 9 shows a modified version of the Colpitts oscillator, known as the Clapp or Gouriet oscillator. Another capacitor, C3, with a value that is small relative to C1 and C2, is put in series with L1. This circuit's resonant frequency is determined principally by the values of L1 and C3 and it is almost independent of variations in transistor capacitance. The Clapp/Gouriet oscillator offers excellent frequency stability. With the component values shown in the schematic, it will oscillate at about 80 kHz.

Figure 10 is a schematic for a Reinartz oscillator. Its tuning coil has three inductively coupled windings. Positive feedback is obtained by coupling the collector and emitter signals of the transistor through coils L1 and L2. Both windings are inductively coupled to L3. The Reinartz oscillator oscillates at a frequency determined by the values of L3 and C1. The coil-turns ratios are typical for a circuit designed to oscillate at a few thousand kHz.

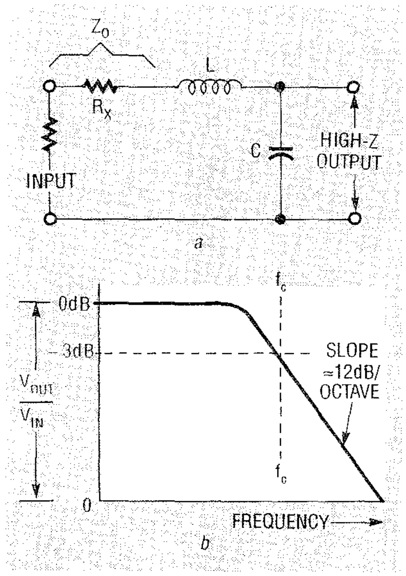

FIG. 12—TRUE L-TYPE LOW-PASS filter: schematic, *a*, and frequency response curve, *b*.

Low-pass and high-pass

Figure 11-*a* is a schematic for a "false" L-type low-pass filter. Inductor L and capacitor C act together as a frequency-dependent attenuator. At low frequencies the reactance of L is low and the reactance of C is high, so the circuit offers negligible attenuation. At high frequencies the reactance of L is high and that of C is low, so the circuit offers high attenuation.

Consequently, the circuit acts like a low-pass filter. It is called it a "false" filter because the circuit will only function correctly if it is driven from a source impedance equal to Z_O. (This is not shown in the diagram.) The circuit is actually a series-resonant filter (like Fig. 1) with its output taken from across capacitor C.

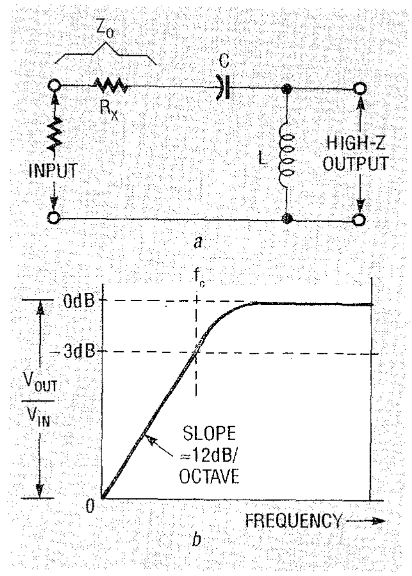

FIG. 13—L-TYPE HIGH-PASS FILTER: schematic, *a*, and frequency response curve, *b*.

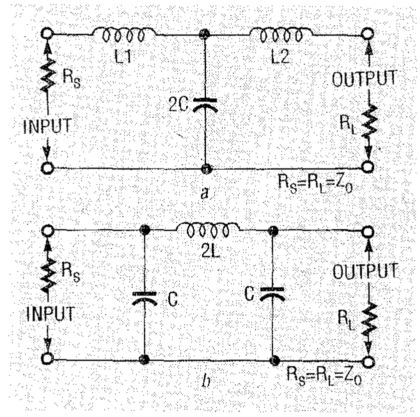

FIG. 14—LOW-PASS LC FILTERS: T-section schematic, *a*, and π-section, *b*.

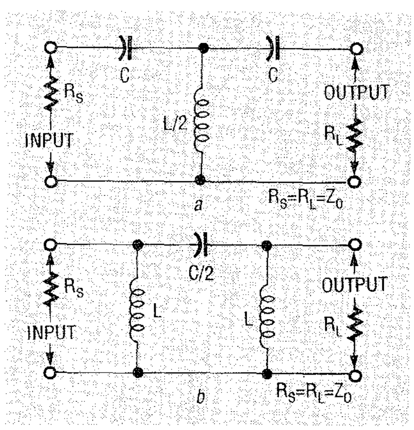

FIG. 15—HIGH-PASS LC FILTERS: T-section schematic, *a*, and π-section, *b*.

If the circuit is driven from a

continued on page 89

duce a required sound-pressure level from a given loudspeaker, it clips the positive and/or negative peaks of the musical waveforms. Short-duration overloads may not be audible; longer overloads are frequently perceived as level compression, rather than distortion. However, badly overdriven amplifiers produce a raspy distortion, not unlike that of a mistracking phono cartridge. Low bass passages are likely to take on a "mushy" quality because of the spurious harmonics generated by the overload. And as discussed earlier, prolonged operation with hard clipping is a frequent cause of driver damage, so clipping should be avoided.

Proper power ratings

Arriving at a speaker system's power rating is no easy task, even for its designer. Ideally, a manufacturer designs for the highest power capability that can be achieved within his cost and size constraints for a given model. Special high-temperature materials such as voice-coil wire, voice-coil forms, and cements all play a part in squeezing the maximum power rating from any given speaker.

The test signal used to derive a system's power rating must be chosen carefully. The ubiquitous pink-noise signal used in so many other audio tests is totally inappropriate for power testing because, unlike music, it has equal energy per octave. In contrast with the midrange energy hump displayed by most music, pink noise shows up on a real-time analyzer as a virtually straight line, which is a poor representation of music.

The single rms ratings used by some manufacturers imply the use of a sinewave test signal, which, again, is totally unlike a musical waveform in shape or energy content. The most valid and informative way for a manufacturer to specify a speaker's power-handling capability is to state, however loosely, the power it can handle in a specific frequency range for a specific amount of time.

Listing specifications that way gives rise to a somewhat complex, but informative, power-handling capability specification, such as that used by Allison Acoustics: "At least 15 watts continuous at any frequency. Over most of the frequency range, at least 350 watts for 0.1 second, 125 watts for 1 second, 60 watts for 10 seconds."

Note the distinctions Allison makes between continuous and transient wattage levels. The difference between them is what allows you to play very loud music without problems, even though a continuous sinewave at the same peak level would certainly damage your audio equipment. In other words, your 100-watt (or even 200-watt) amplifier is certainly safe to use with typical speakers rated at 50 watts maximum so long as you don't feed continuous tones or pink noise to them, drive the amplifier into hard clipping, drop a tone arm, or lose a cable ground at high volume. In short, you have to abuse your speakers (and your ears) before disaster is likely to strike. If you don't ask for trouble, it probably won't happen. Ω

L-C FILTERS

continued from page 72

low-impedance source, the output will produce a steep signal peak at f_c, as shown in the frequency-response curve of Fig. 11-*b*. The magnitude of this peak is proportional to the circuit's Q.

Figure 12-*a* shows how Fig. 11-*a* can be modified so that it behaves like a true L-type low-pass filter. Resistor R_X is placed in series with the circuit's input so that the sum of R_X and R_S (the input signal's source impedance) and R (the equivalent resistance of L) equals the circuits characteristic impedance Z_O. The addition of this resistance reduces the circuit's Q to unity, but it results in a clean low-pass filter output shape as shown in Fig. 12-*b*.

Figure 13 illustrates how the principle just discussed can be applied to make an efficient L-type high-pass filter. The output is taken across inductor L rather than across capacitor C. The value of equivalent resistor E_X in both of these circuits can be reduced to zero if the filter's Z_O value is selected to match R_S, as given in formula 2 of Table 1. The outputs of these filters, like those of the series and parallel-resonant filters, must "see" only high-impedance loads to operate properly.

The most popular low-pass and high-pass filters are balanced, with matched impedances that are designed to be driven from, and have their outputs loaded by, a specific impedance value. Such filters can readily be cascaded to yield very high levels of signal rejection. Among those filters are the T-section and pi-section low-pass filters that are shown in Fig. 14, and the T-section and pi-section high-pass filters that are shown in Fig. 15.

All of these filters exhibit an output rolloff of about 12 dB per octave (40 dB per decade). Their outputs must be correctly loaded by a matching filter section or terminating load. The design formulas for them are given in Table 1.

Figure 16 shows an application for a T-section low-pass filter—an AC power-line filter that will block interference that is on the line from reaching a sensitive unit of equipment while also blocking any interference from that might be generated internally by that unit from reaching the power lines. This circuit can be made to operate at frequencies up to about 25 MHz. Ω

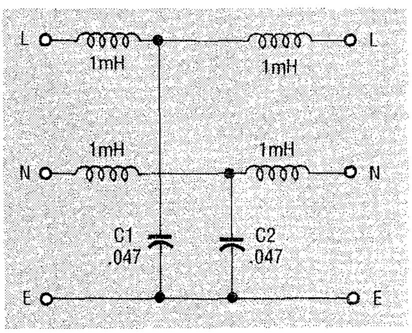

FIG. 16—T-SECTION POWER LINE input filter rejects interference on the power line to about 25 MHz.