Stabile high-Q inductors are critical in frequency-hopping radios

High Q is an important contributor to tuned circuits transmitting a sharp, clear signal while the frequency is changed several times a second. Designing tunable coils that maximize Q and are stable with temperature is essential for increasingly tight tolerances required by platforms such as those for software-defined radio.

By Rich Barden

Secure communication has come a long way since the U.S. Marines used Navaho in the Pacific Theater of WWII so enemies could not make use of intercepted radio messages. The latest versions of military radio use frequency-hopping technology to thwart enemy eavesdropping. While coded digital instructions are included in the transmission to coordinate the frequency hopping between radios, a clear and ungarbled voice signal still must be transmitted and received in a conventional sense.

Lodestone Pacific's variable shielded-coil-form product line has been an integral part of the ITT SINgle Channel Ground and Airborne Radio System (SINCGARS) for more than 10 years (shown in operation in Figure 1). This latest technology tactical radio operates between 30 MHz and 88 MHz, with 2320 channels. The demands on the radio's LCR (inductor-capacitor-resistor) tuned circuits become more stringent as voice and data are switched among many frequencies per second in the heat, humidity, vibration and rigors of the combat environment.

To maintain a 0.02% tight frequency tolerance in this demanding application, the quality factor, or Q factor, of the tuned circuit is critical. The Q factor of a tuned LCR resonant circuit is a measure of the sharpness of the response curve, and maximizing the Q factor in tuned circuits is a bit of an art. The higher the Q value, the higher the energy at that specific frequency, and the sharper the response. The amount of Q in a radio's tuned circuits must be carefully considered. If too high (and tight), some of the modulation's spectrum will be cut off. If the Q is too low, (with a wide peak), other signals and excessive noise will get through. It is best to use the highest Q inductors and capacitors available, since a Q that is too high can be reduced by intentionally introducing resistance in the circuit, while circuit modification to improve the Q of a low-quality inductor will add noise to the circuit.[1]

Obtaining high Q

In a tuned LCR circuit, either the inductor or capacitor will need to be adjustable. In the ITT SINCGARS radio, several Lodestone Pacific tunable-shielded-coil-form inductors, wound by Datatronics, are used to achieve the highest and most stable Q. The optimum Q of a tunable assembly is found in balancing the fundamental physics of the core material and the wire winding around the core. The key to optimizing the Q of the assembly is selecting the proper core material, wire, and its winding characteristics for a particular frequency.

Core material

The quality and characteristics of the magnetic field generated in the variable inductor are determined by the quality and shape of the magnetic core material. A cylindrical core in the center of a spring-wound wire coil form will create a magnetic field that surrounds the core and winding. The construction of the variable shielded assembly uses either iron-powder or ferrite-shield cups to trap and channel the

Figure 1. The SINCGARS radio from ITT provides secure tactical voice communications through frequency hopping.

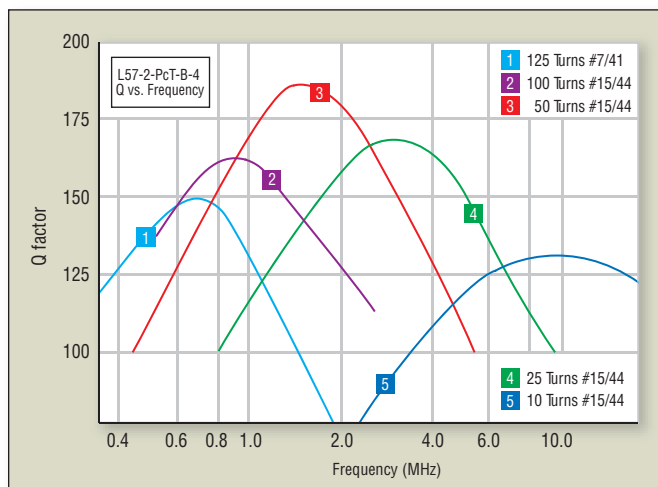Photo by Staff Sgt. Charles B. Johnson, courtesy of U.S. Army.

Figure 2. Q vs. frequency for the L57-2-PCT-B-4 family.

lines of flux within a closed magnetic pathway, increasing the efficiency and performance of the assembly.

The more complete the magnetic pathway along the magnetic lines of flux, the higher the inductance and the Q of the assembly. The optimum state for a tuned inductor is to have the desired inductance reached when the gap between the tuning core and the like-material shield cup is minimized.

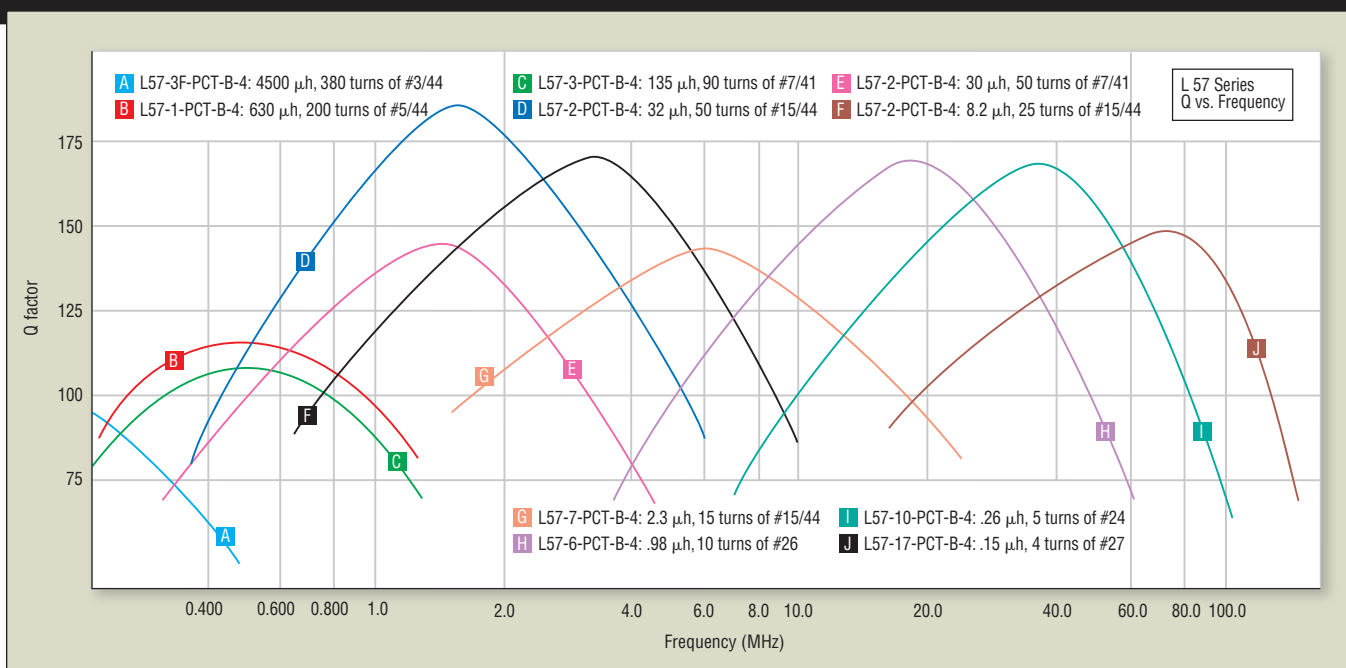The inductance (L) of the coil is affected by the permeability of the

A L57-3F-PCT-B-4: 4500 μh, 380 turns of #3/44
B L57-1-PCT-B-4: 630 μh, 200 turns of #5/44
C L57-3-PCT-B-4: 135 μh, 90 turns of #7/41
D L57-2-PCT-B-4: 32 μh, 50 turns of #15/44
E L57-2-PCT-B-4: 30 μh, 50 turns of #7/41
F L57-2-PCT-B-4: 8.2 μh, 25 turns of #15/44
L 57 Series Q vs. Frequency

G L57-7-PCT-B-4: 2.3 μh, 15 turns of #15/44
H L57-6-PCT-B-4: .98 μh, 10 turns of #26
I L57-10-PCT-B-4: .26 μh, 5 turns of #24
J L57-17-PCT-B-4: .15 μh, 4 turns of #27

Figure 3. Q vs. frequency for the L57 series.
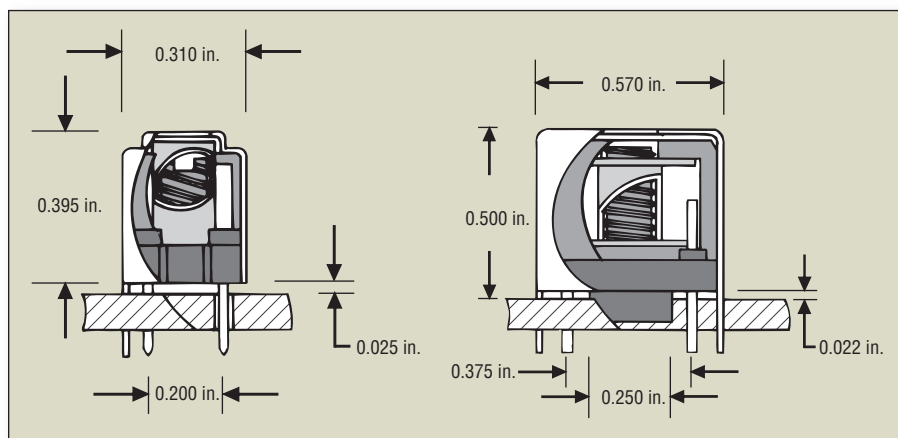
Figure 4. The L33 assembly (left) has less core material and, therefore, lower Q potential than the L57 assembly (right).

Mix Number	Color Code	Magnetic Material	Material Permeability	Frequency Range (MHz)	Temperature Stability (ppm/°C)
1	Blue	Carbonyl C	20.0	0.15 to 2.0	280
2	Red	Carbonyl E	10.0	0.25 to 10	95
3	Grey	Carbonyl HP	35.0	0.02 to 1.0	370
3F	Grey/orange	HP/ferrite	80.0	0.01 to 1.0	700
6	Yellow	Carbonyl SF	8.5	2.0 to 30	35
7	White	Carbonyl TH	9.0	1.0 to 20	30
10	Black	Carbonyl W	6.0	10 to 100	150
17	Lavender	Carbonyl W	4.0	20 to 200	50
50	Orange	Ferrite 50	125.0	0.01 to 1.0	1500
60	None	Ferrite 60	125.0	1.0 to 120	1500

Table 1. Iron powder core material properties for various Lodestone-Pacific mix numbers.

of iron-powder core materials supplied by Micrometals for Lodestone Pacific's tunable, shielded-coil-form product line.

The manufacturer of each core part number will have an inductance rating called an A_L value, which is expressed in nanohenries per turn squared (nH/N2). When the A_L is known, the number of turns of wire required for a desired inductance can be calculated from the following formula:

Required turns = [desired L/A_L]$^{1/2}$

Where L is the inductance in nanohenries (nH). The Micrometals iron-powder materials, or mixes, used in assemblies for the ITT SINCGARS radio are formulated for optimum Q within specific frequency ranges.

Q vs. frequency curves are used to describe Q magnitude across a range of frequencies. The shape of these curves can be characterized by the following formula:

$Q = 2\pi fL/R$

Where f is frequency in megahertz (MHz), L is inductance of the assembly in microhenries (μH), and R is the effective series resistance for the heat losses contributed by copper losses and core losses, measured in Ohms (Ω). The formula shows how important low resistive loss in the winding and core material are to high Q factors.

While the frequency and inductance are known (or can be calculated), the frequency-sensitive copper losses and the core material losses are often difficult to measure. In addition, variations in core materi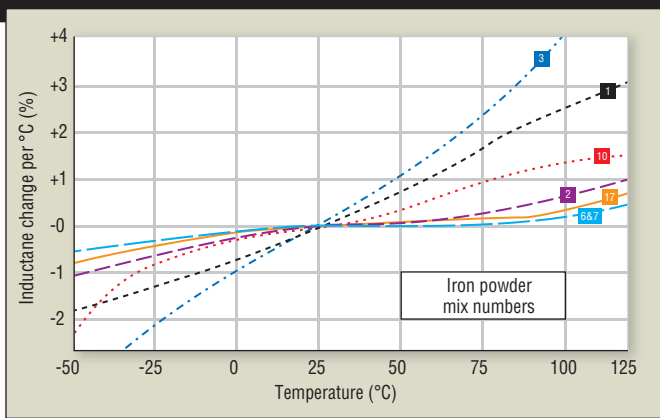al density and winding characteristics often cause the Q factor experienced in actual applications to differ from results predicted by theory.

The Q vs. frequency curves in Figures 2 and 3 are plotted on a semi-

core material and the number of turns of wire around the core. In the ITT SINCGARS radio, iron-powder core materials are used because of their superior temperature stability. Table 1 shows the properties

Figure 5. Iron-powder core materials show great stability across temperature for rated inductance.

Figure 6. In addition to stable inductance (see Figure 5), iron-powder core materials show great stability across temperature for rated Q.

log axis and were derived from actual testing of the variable assemblies in a parallel-resonant circuit, and reflect the expected Q readings with a fixed inductance and specific winding. As the frequency is varied, the readings will trace a humped curve showing how Q will vary with frequency. Changes to the inductance of the assembly (and the loss) caused by changing the tuning position or altering the winding will produce a new Q curve.

Increasing inductance by adding turns of wire or tuning the core toward the maximum inductance position will create a new Q curve, with a peak that will be shifted down in frequency. Conversely, reducing inductance by decreasing turns or de-tuning the assembly will shift the Q-curve peak toward a higher frequency.

Figure 2 shows the Q factor as a function of frequency for the Lodestone Pacific L57-2-PCT-B-4 assembly wound with different numbers
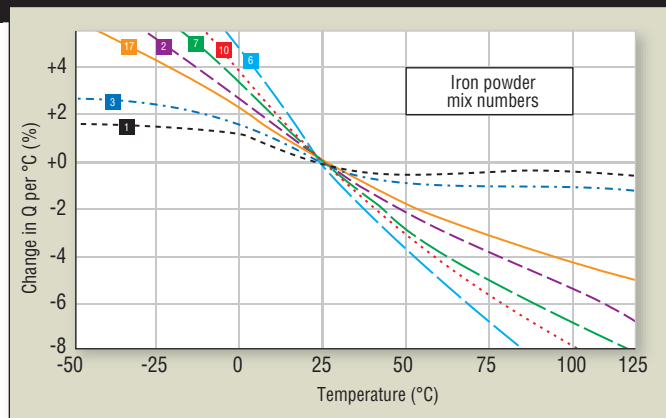
of turns. This family of Q curves shows the trend toward higher-frequency Q curves as inductance is reduced through the reduction of turns. It also shows that the maximum value of each Q curve will diminish as the curve peaks move to the extremes of their recommended frequency ranges. There is an optimum frequency and inductance combination for a given assembly where the "peak of the peaks" will occur (at 1.5 MHz in Figure 2). This is why applications requiring high Q are best engineered with the inductive portion of the tuned circuit optimized first, and the capacitor specified to support that optimum Q.

Each iron-powder core material formulation will produce similar families of curves within their optimum frequency ranges. The complete family of Q curves for the L57 series on Figure 3 show that iron-powder mix formulations 6 and 10 (shown in curves H and I) exhibit better Q characteristics as the frequency moves from 2 MHz (mix 2's optimum

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frequency range as indicated by curve D), to 20 MHz and 40 MHz.

Increasing the amount of core material in the assembly will also improve Q. As an example, the L57-2-CT-B-4 wound with 25 turns of 15/44 Litz wire will produce higher Qs than the L33-2-CT-F-4 with the same winding. This is due to the fact that the iron-powder content in the larger L57 shielded assembly (4.45 grams of core material) is nearly seven times greater compared to the L33 assembly, (0.601 grams), as can be seen in Figure 4. The more core material used in the assembly, the higher the inductance and the greater the potential Q.

Winding considerations

The type and size of the wire used in the winding is frequency sensitive. This is due to the losses that result in the electronic and magnetic fields emitted from the wire in the winding. As frequency is increased from 100 kHz to 1 MHz, the resistive eddie current losses in the wire and the skin effect at the surface of the wire become significant. The skin effect describes the phenomenon whereby the current concentrates on the outer region of the wire's cross section, and thus increases the total resistance of the wire. It is possible to minimize this effect by dividing the conductor into a bundle of interwoven insulated strands called Litzendraht (or Litz) wire. The strand diameter is matched to the frequency so that the skin effect in the individual strands is negligible.

Litz wire is described as 7/41 (seven strands of 41 AWG), or 15/44 (15 strands of 44 AWG.) and will tend toward larger bundles of smaller strands as frequency is increased. Above 1 MHz, the advantages of reduced resistance using Litz wire are nullified by the disadvantages of increased capacitive losses created by the parasitic capacitance among the wire strands. As the capacitance of adjacent turns, as well as the capacitance from the winding to the core, becomes significant, stranded wire should be abandoned in favor of heavier solid wire. Thus, higher-frequency windings will tend toward fewer well-spaced turns of larger-diameter, enamel-coated magnetic wire.

It is also evident that 50 turns of 15/44 is a more efficient Litz winding than 50 turns of 7/41 on the L57-2-PCT-B-4 tuned to 30 µH at 1.5 MHz (Figure 3, curves D and E). As the capacitive effects begin to dominate, the Litz wire becomes a liability. The exact frequency is dependent on the application, but the practical transition is from 1 MHz to 10 MHz.

Temperature stability

An important characteristic of iron-powder core materials is the outstanding temperature stability. The temperature stability information for each iron powder mix is listed in parts-per-million per degree Celsius (ppm/°C) in Figure 1. As an example, the inductance of a 100 ppm/°C material will change by 1% over a temperature change of 100 °C.

Figures 5 and 6 plot the temperature stability for iron powder materials as a percentage change in inductance and Q factor, respectively. Iron powder core materials have excellent temperature stability from –65 °C up to x125 °C. Ferrite materials are more sensitive to temperature and will exhibit changes in inductance and Q from five to 10 times greater than iron powder over the same temperature range.

In an iron-powder core, inductance will increase gradually as the core material's temperature increases from 25 °C to more than 100 °C. With continuous operation above 100 °C, inductance and Q will begin to degrade with time. The extent of this shift is dependent on time, temperature, and frequency. Iron powder cores tolerate temperatures down to –65 °C with no permanent effects.

Extended periods of elevated temperature will result in a permanent shift in inductance and Q when the assembly is returned to ambient. For temperature-sensitive applications up to 100 °C, this shift can be stabilized by artificially aging the core material at 100 °C for a minimum of 48 hours.

Designing a high-Q tuned circuit requires an understanding of how to maximize the properties of an inductor's magnetic field while minimizing the resistive losses in the wire and the core. Because both these properties are frequency sensitive, designing a tuned circuit for a radio that has more than 2000 channels is no minor task. When you consider this radio needs to be dependable in a dirty and harsh environment that will include wide temperature swings, significant vibration and repeated shock, the value of these high-Q inductors in such designs is obvious. **DE**

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References

1. Daniel Talbert, "2nd Order Low-pass Notch Networks-What the Text Books Don't Tell You."

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Rich Barden is founder and president of Lodestone Pacific. He has been in the magnetics industry for more than 25 years and is active in industry organizations in the United States and Asia. Barden has a B.S. in Economics and a Masters in Business, both from UCLA. Barden can be reached at richbarden@lodestonepacific.com.