Inductance Standards and Decades

Construction An inductor with a non-magnetic core (called an "air core") will have higher stability and negligible non-linearity compared to one wound on a core made of a high-permeability alloy (referred to as an "iron core" even if the alloy contains little, or no, iron). However, an air-core coil will have a relatively low Q. Because stability is the prime requirement of a laboratory standard, the GR 1482 Standard Inductors are wound on ceramic forms that magnetically act like air.

For circuit design and other experimental work, a higher Q is preferable, even at the expense of stability and linearity. Therefore, the GR 1491 Decade Inductors use iron cores. A good balance between these opposing characteristics is possible, however, with cores made from certain powdered alloys so that these decades can maintain good accuracy with time and over a reasonable current range. All GenRad inductors use cores of toroidal shape which generate a very low external field and are relatively immune to pickup from external fields. Coils of this shape can be placed close together with negligible mutual inductance. The symmetry of the toroidal shape also contributes to stability and a constant temperature coefficient.

Inductance Changes The inductance depends not only upon the geometry of the winding and the permeability of the core but also upon the residual impedances that are shown in the equivalent circuit of Figure 1. The largest changes of inductance with frequency are produced by the effective shunt capacitance, C_o, of the winding and the terminals. Any capacitance increases the effective inductance value as the resonant frequency is approached:

$$L = \frac{L_o}{1 - \omega^2 L_o C_o} \qquad (1)$$

where L_o is the zero-frequency inductance. The inductor will appear capacitive above resonance. When the frequency is well below the resonant frequency, $f_r = \frac{1}{2\pi\sqrt{L_o C_o}}$, the fractional increase in inductance is

$$L \simeq L_o\left[1 + (f/f_r)^2\right] \qquad (2)$$

The resistances shown in Figure 1 also affect the inductance value and make the effective series and parallel inductance values somewhat different, particularly when the Q is low: $L_p = L_s\,(1 + \frac{1}{Q^2})$.

Air-core inductors change very little with current, but the permeability of ferromagnetic materials depends upon the ampere turns of magnetizing force applied. The inductance rises linearly over a small region near zero current, then more rapidly to a maximum, followed by a suddes decrease as saturation is approached. To make these curves independent of inductance value, the current has been normalized to a value I_1, which is the current that produces a specified fractional increase in inductance.

Q vs Frequency The storage (or quality) factor, Q, is the ratio of reactance to resistance and is infinite for a pure inductance. If the resistance is all true series resistance (R_C in Figure 1) and the inductance is constant, then the Q is proportional to frequency: $Q = \omega L/R_C$. But as noted above, L changes with frequency and also there are other sources of loss. The components of loss can best be described in terms of the dissipation factor, $D = 1/Q$, because the total D is the sum of the component D's, and these can be plotted as straight lines in logarithmic coordinates, as shown in Figure 2. For an air-core coil, the other sources of loss besides the ohmic or "copper" loss are eddy current loss, in any nearby conductors (such as a case) and in the wire itself, and dielectric loss, in the stray shunting capacitance (shown lumped as C_o).

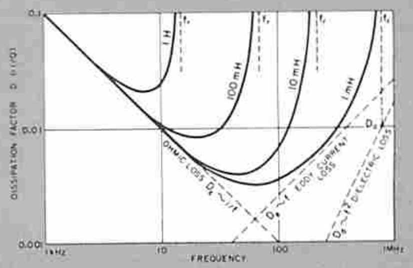

Figure 2. Dissipation-factor variation with frequency in typical air-core 1482 Standard Inductors.

$$D \simeq \frac{1}{1 - (f/f_r)^2}\left[\frac{R_C}{\omega L_o} + G_e\omega L_o + (f/f_r)^2 D_o\right] \qquad (3)$$

Resonance Factor — Ohmic Loss D_C — Eddy Current Loss, D_e — Dielectric Loss, D_d

The higher permeability obtained by using an iron core allows fewer turns for a given inductance, reducing R_c and C_o and increasing f_r. The core adds two more components to the dissipation factor: one from eddy current loss in the core, which increases D_e, and another from hysteresis loss in the core, which depends on flux density.

Calibration The calibrated inductance of a standard inductor is the change in the measured inductance of a circuit when a portion of that circuit is removed and replaced by the inductor. This measured inductance includes small and variable mutual inductances between the inductor and the rest of the circuit, which are negligible when the calibrated inductance is larger than, say, 100 microhenrys, but which can introduce accuracy-limiting uncertainties into the calibration of smaller inductances. These uncertainties can be reduced to less than one nanohenry to permit accurate calibrations down to one microhenry, if the mutual components are made a definite part of the calibrated inductance. One method of achieving this, used in the 1482 Standard Inductors of 200 microhenrys and less, is to provide, on the inductor, a switching link, which connects either the inductor coil or a short circuit through internal leads to the external connection terminals. The calibrated inductance, which is the measured difference of the connection terminals when the switch is moved from coil to short, is to a high degree independent of the external connections or environment.

Since the inductance usually varies with frequency, an accurate calibration requires that the frequency be specified. When, as in inductors with iron cores, the inductance also varies with current, the calibration must also specify a corresponding current or voltage. Since the frequency or current at which the inductor will be used is not usually known, a convenient reference level is zero frequency and zero current (initial permeability). Measurements made at two currents within the linear range and at well below resonant frequency are extrapolated to obtain inductance at zero current and initial permeability of the core material.

Figure 1. Equivalent circuit of an air-core inductor. R_C is the series resistance, G_e is the conductance due to eddy-current loss, and D_o is the dissipation factor of the distributed capacitance.