About Q,

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In the crystal radio hobby – and in electronics in general – "Q" can refer to a number of things: the Q of a coil, the Q of a circuit, the quality factor of some item, or the label of a transistor on a schematic (e.g. transistor Q1). Most of the time, when crystal hobbyists say Q, they mean the Q of a coil, Q of a variable capacitor, Q of an RLC tuned circuit, or Q of a whole crystal set. Q of the set is important because it determines the selectivity of the set. With a low-Q set one can hear many stations at one dial setting; with a high-Q set one can select or "isolate" listening to one or a few stations.

For an RLC circuit, Q is a measure of the energy stored in the circuit to the energy dissipated per RF cycle. Loading by an antenna and detector (diode and audio components) - that is, adding resistance - increases losses and thus decreases Q.

So how do we sort all of this out? What can we use to improve our sets? Perhaps the best starting point is to list the common definitions of Q and discuss their uses and benefits. Then we'll describe how to measure Q on the bench.

Q of a Coil. The Q of a coil is defined as its inductive reactance divided by its resistive losses at a specified frequency:

(1.1) $$Q = \frac{2\pi fL}{r} = \frac{XL}{r},$$

where *f* is the frequency in Hz, L the inductance in Henries, X is the reactance of the coil, and r the series resistive losses in the coil.

Q of a Series RLC circuit: A series resonant RLC circuit is known to step up the voltage across the inductor, compared to the applied voltage to the whole. The Q of a series RLC resonant circuit can be written as:

(1.2) $Q = \frac{|V_L|}{|V_{in}|}$,

where V_L is the voltage across the coil and Vin is the supply voltage.

Q of an RLC resonant circuit. The generic definition of Q for a series or parallel RLC tuned circuit is:

(1.3) $Q = \frac{f_0}{f_2 - f_1} = \frac{f_0}{bandwidth}$,

where f_0 is the resonant frequency of the circuit, f_2 the frequency at the half-power point above resonance, and f_1 the frequency at the half-power point below resonance. A half-power point is the frequency wherein the power of the signal is ½ that at the resonant frequency.

Q in General. Q can be defined for electrical and mechanical systems as follows:

(1.4)

$$Q = (2\pi)\frac{energy\ stored}{energy\ dissipated\ per\ cycle}.$$

Q Design Formulas. Q formulas have been developed over time that model or fit experimental data taken. For example (from RDRE, see reference), the Q of an air core solenoid using bare copper solid wire (where the wire diameter, d, is .4 to .8 the distance between windings – called pitch) is roughly:

(1.5)

$$Q = AD\sqrt{f},$$

where A is a function of coil length/diameter (and is 100 for length/D=1), D is the mean diameter of the turns, f is the frequency in MHz.

How can we use these equations?

Equation (1.1) can be used to estimate coil Q but the resistance is generally not known for a particular frequency and solenoid or other coil arrangement. The losses include resistance losses in the wire turns due to the skin and proximity effects and losses in any dielectrics associated with coil and environmental capacitances.

Equation (1.2) can be used to quickly estimate the Q of a series resonant circuit given one has a generator and scope to measure both voltages. Generator or scope probe impedance will alter results in most cases. The generator resistance will limit Q for HF applications.

Equation (1.5) is useful in that it provides some direction on coil size given frequency. But it offers nothing regarding form and wire losses, so will estimate Q high.

Equations (1.3) and (1.4) are used, with proper equipment, to measure both series and parallel RLC circuits and coil Qs. In fact, (1.3) is the basis for the Half-Power Bandwidth Method (HPBM) of measuring Q. In addition, Equation (1.4) is the basis for the Ring-Down Method (RDM) of measuring Q. The HPBM is described below. The Ring-Down Method is outlined in another article on this website.

Figure 1 displays a bench arrangement for measuring coil Q using HPBM. The following equipment is required:

- a stable HF generator with digital frequency readout,
- a scope with adequate bandwidth, 10 MHz or better,
- a high-Q variable capacitor or moderate-Q cap with known losses,
- a launch coil to provide a source for the coil under test (UUT),
- and a 1X probe to clip on the UUT for signal pickup.

Figure 1: Q Measurement Bench Setup

For example, our bench has a B&K Precision 4017B DDS/Sweep Function Generator capable of driving a 50 ohm load with up to 10 VPP from DC to 10 MHz. The scope is a Tektronix 150 MHz with dual traces and cursors to measure frequency and time. We use an XSS 365 cap with known losses versus frequency and rotor position or a combination of mica caps to resonate the coil at any given frequency. For the driver coil, we use a 3.5 inch diameter by 1 inch piece of ABS pipe for the driver coil form and 13 turns of #22 magnet wire, connected in series with a 50 ohm resistor to the generator output. The 1X probe is simply a piece of coax with clips on the end for attachment to the cold and hot ends of the coil (UUT). The driver coil is positioned about 6-inches from the UUT to begin with and then moved farther away if sufficient signal is present. The scope probe is clipped onto the insulation of the wire coming off the coil's hot end (presenting less than 1 pf to the coil). The driver coil and UUT are placed above a grounded metal plate and separated from the walls by about three feet. It's not a perfect bench setup but works fine for our moderate-Q coil measurements.

The following describes the Q measurement of a single-layer 250uH coil using HPBM. The coil inductance was calculated, using the Wheeler equation (see the equations page on the website). The coil parameters were: 3.5" ABS form, #24 AWG hookup wire with outside PVC dia = 0.05", turns, N = 61, length = 3.05".

- The generator was set to 600 kHz and attached to the driving coil,
- The variable capacitor was tuned to achieve a peak on the scope,

- The generator amplitude was adjusted so that peak-to-peak voltage (ppv) was seven display segments,
- Generator frequency was increased until the ppv dropped to 5 screen segments (~.71 peak, one of the two half-power points), and the frequency was noted.
- The generator frequency was then decreased until the scope signal peaked and then fell again to 5 segments, and the frequency was noted.
- Q was then calculated using equation (1.3).

Results are noted below.

Freq kHz	Bandwidth	Calc'd Q	Cap Q	Adjusted Q	% adjust
		Q1	Q2	Qcoil	
600	2.5	245	4000	261	7%

Measurements indicated a Q of 245 for the UUT in the bench arrangement. This is not, however, the Q of the coil since losses in the variable cap, in stray capacitances, and due to probe loading are present. Assuming the probe and stray capacitance loading is minimal, we've estimated the Q of the coil by subtracting the losses due to the variable capacitor. These Qs are related by the following equation:

$$\frac{1}{Q_m} = \frac{1}{Q_{coil}} - \frac{1}{Q_{cap}}, \text{ or rearranged } Q_{coil} = \frac{Q_{cap}Q_m}{Q_{cap} - Q_m},$$

(1.6)

$$\text{hence, } Q_{coil} = \frac{4000 * 245}{4000 - 245} = 261.$$

Equation (1.6) can be derived by transforming RC and RL series circuits connected in parallel into a single parallel RLC circuit.

So you can see that set Q and coil Q are prime parameters of a crystal set. It's for this reason that set builders are known to wind, measure, and try many coils. The goal is to reduce losses in the coil and set in order to achieve or maintain a set with high total Q (and narrow bandwidth/good selectivity). We can see that this is not easy to do if we rearrange equation (1.3) as follows:

(1.7)

$$bandwidth = \frac{f_o}{Q}.$$

Clearly, as the tuning frequency is increased, Q must be increased if we expect to maintain our bandwidth (selectivity). One strategy used to overcome this obstacle is to segment the crystal set into several sub-band sets, say 500 to 800 kHz and 800 to 1600 kHz, and use different coils for each. Another strategy, if inexpensive parts are being used – a budget set if you will, is to use one smaller value of inductor for the whole set and switch in extra capacitance for the lower portion of the band. This arrangement avoids using the small capacitance portion of the variable capacitor wherein its losses are much greater as frequency rises.

References:

(1) RDRE, Reference Data For Radio Engineers, Sixth Edition, 1975, H.W Sams, page 6-4.
(2) www.midnightscience.com/formulas-calculators.html
(3) www.midnightscience.com/article-index.html

