# Crystal characterization and crystal filter design

An overview of techniques and tools

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## Purpose & scope

This paper was prepared to parallel a PowerPoint presentation I developed for the OzarkCon QRP convention in Joplin, MO. PowerPoint slides are fine as presentation guides, but typically don't contain sufficient detail for use as a stand alone reference paper.

In this paper, I'm reviewing the techniques for measuring crystal parameters as found in a number of published articles, typically ham related. I'm also discussing the instrumentation required, which I consider to be of minimal cost and complexity considering the task. The two major techniques I call the BW / Q method and the shifted frequency method. In the former, a signal generator and detector are used to determine the crystal's 3 dB bandwidth and its loss resistance is found by substitution. This is enough information to calculate the key parameters of the crystal model.

With the shifted frequency method, the crystal is installed in an oscillator circuit and the effect of switching a known capacitance in and out of series with the crystal is noted. This allows calculating the motional inductance and capacitance easily.

In the second major section, I discuss crystal filter design. The detailed theory and mathematics of filter design is beyond the scope of this article in general. Rather, I focus on use of two popular and easily available software packages for filter design. Some practical aspects of filter design and construction are covered. The merits of various filter shapes or response types (Gaussian, Chebyshev, etc.) are discussed qualitatively.

## Introduction

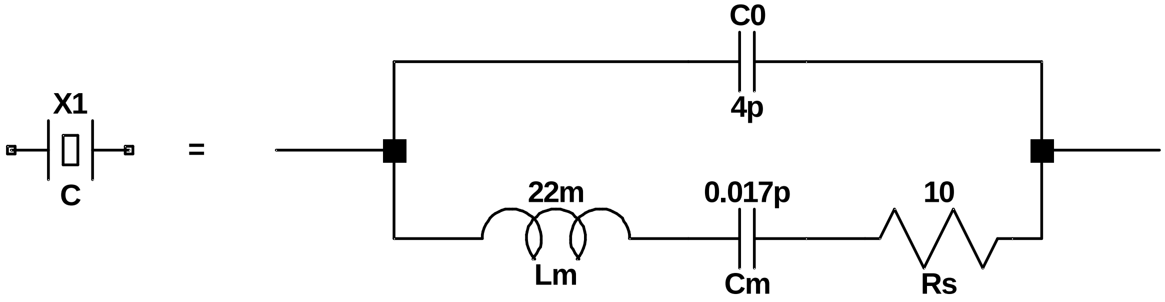
The crystal filter has long been a key component in the design of "single signal" superheterodyne CW receivers and other highly selective receivers regardless of mode, as well as in the generation of single sideband signals using the so called "filter type" method. For some time, the design and construction of these filters has been largely the domain of commercial entities. Only the most advanced hobbyists having knowledge and equipment out of the reach of most average homebrewers attempted it. In the past couple of decades however, a number of advancements have put the design and construction of crystal filters within the capabilities and pocketbooks of the typical ham builder. These advancements, which I intend to overview, include the following:

- Publication of key papers by Hayward, Demaw and others*, which described simple test equipment and procedures for crystal measurement and filter design. (*In the UK, J.A. Hardcastle and Dave Gordon-Smith published techniques.) Emphasis on ladder type filters using all crystals on the same frequency was a key factor in reducing cost and complexity.
- Availability of inexpensive, highly stable signal generators adjustable to 1 Hz resolution including DDS, PLL and VXO types.
- Availability of free software capable of designing crystal filters of various types quickly and easily.

- Availability of free software to model and plot the response of proposed filter designs, allowing repeat analysis and “what if” testing before committing to hardware.
- Availability of inexpensive crystals on a wide variety of frequencies, often priced at fifty cents or less each from large retailers, and possibly even less from surplus sources.

## Crystal characterization

Characterization just refers to measuring the electrical parameters of the crystal. But what are the expected parameters of a wafer of a mineral placed between two electrodes? Fortunately, a model consisting of elements we know how to deal with (C, L, R, f) can be used to approximate the device’s behavior in a circuit to a high degree of accuracy when near the resonant frequency of the crystal.



**Equivalent circuit of a crystal**
**Lm = motional inductance**
**Cm = motional capacitance**
**Rs = equivalent loss resistance**
**Co = holder capacitance**

### The model of a crystal

The simplest model of a crystal is that of a series resonant L-C circuit. To allow for the fact that crystals have finite Q, we add an equivalent series loss resistance Rs. And finally, consider the fact that the wafer of crystal is held or contained between two metallic plates or depositions of metal. These parallel plates naturally form a capacitor, which appears in parallel with the L-C-R model of the crystal itself. This adds the fourth element to the complete model, Co. The L and C of the series model are called Lm and Cm with the subscript from the fact that they are referred to as the *motional* parameters of the crystal. The values in the figure are typical of an 8 MHz HC-49/U crystal.

### Measurement Methods

### #1 – Bandwidth & Q Method

This method uses the fact that a series R-L-C circuit will have a certain 3 dB bandwidth around its resonant peak. (Note that parallel capacitance doesn’t affect this measurement method and isn’t determined by it.)

Two formulas expressing the Q of the R-L-C series circuit model can be used to determine Lm and Cm. A measurement of Rs is also required for this method. Those expressions for Q are:

(1) $$Q = \frac{f_R}{BW}$$ and,

(2) $$Q = \frac{X}{R}$$

Where $f_R$ in (1) is the resonant frequency and BW is the bandwidth at the -3 dB points.

In (2), X is the reactance of Lm or Cm (they are equal at resonance) and R is the total series resistance of the circuit. The "R" value in this equation bears some more explanation, as it is usually more than just the $R_S$ of the crystal. In the typical measurement scheme, a signal generator of source resistance $R_g$ drives the crystal and a detector generally having the same resistance is connected to the opposite end of the crystal. Thus the complete circuit has resistance $R_g + R_s + R_g$, or $R_s + 2 R_g$ total resistance. The Q measured in this way is called the *loaded* Q because it includes not only the crystal's loss resistance but also the source and load resistances of the circuit.

Now, how are these facts used to measure crystal parameters? The signal generator, crystal, and detector are connected in series. The point of the peak reading on the detector is found and noted as the resonant frequency. Then the frequency is varied below and above that frequency to find the points where the detector shows ½ of peak power (-3 dB points). Subtracting the lower from the higher frequency gives the bandwidth. Now we have enough information to calculate the loaded Q from (1).

Next, $R_s$ is measured by adjusting the frequency to the peak (series resonant) point and noting the reading. Recall that at this frequency, the inductive and capacitive reactances cancel each other so the total impedance of the crystal is simply $R_s$. The crystal is removed and a pot inserted in its place. The pot is adjusted to give the same reading on the detector as just noted. Then the pot's resistance is measured. It is equal to $R_s$.

Now we have enough information to solve for X in equation (2). R is $R_s + 2R_g$ as noted earlier, and Q was determined from (1).

Knowing X, we can now calculate Lm and Cm from the formulas for inductive and capacitive reactance at the resonant frequency.

Lm = X/(2*PI*f) and Cm = 1/(2*PI*f*X)

OK, but we don't want to work through all these individual calculation steps each time we measure a crystal, so we come up with one formula for Lm and one for Cm using our measured data in one step:

(3) $$C_m = \frac{f_1 - f_2}{2\pi * f_1 f_2 R_T}$$

where f1 and f2 are the upper and lower -3 dB frequencies and $R_T$ is the total resistance of crystal, signal generator and detector. Note that the resonant frequency squared can be used in place of the f1*f2 term in the denominator with essentially no loss of accuracy.

And for Lm we have,

(4) $$L_m = \frac{1}{4\pi^2 f^2 C_m}$$

An alternate method of measuring or calculating $R_S$ is available if the test equipment allows measurement of the loss of the crystal at resonance, in decibels. (Ref. 12) This is the difference in detected power to the load with the crystal at resonance and with a jumper installed in place of the crystal.

(x) $$R_S = 2R_g\left(10^{\frac{\alpha}{20}} - 1\right)$$

Where $\alpha$ (alpha) is the loss in dB and Rg is the source or load resistance, assumed to be equal.

## #2 - Shifted Frequency Method

"The G3UUR Method" for measuring Lm and Cm is considerably simpler in that neither a signal generator nor a detector is required. Only a simple oscillator circuit and frequency counter are used.

With this method, the crystal is installed in a Colpitts oscillator circuit. The circuit allows grounding the low end of the crystal directly or through a small capacitor $C_s$ (much smaller than the Colpitts divider capacitors). Frequency measurements are made with the capacitor in circuit and out of circuit and the delta between them is calculated. Cm and Lm are then calculated using the following:

(5) $$C_m = 2(C_s + C_o)\frac{\Delta f}{f}$$

and

(6) $$L_m = \frac{1}{(2\pi f)^2 C_m}$$

This method is simple and fast, but it does not provide a value for $R_S$. Note that some published versions of equation (5) omit $C_o$. This is probably unintentional, since its effect is significant.

The equations above neglect the effect of the Colpitts voltage divider capacitors, since they are large with respect to $C_s$. But in the interest of maximum accuracy, I derived this version of equation (5) which includes those capacitors:

$$C_m = \frac{(f_1^2 - f_2^2)(C_1 C_2)}{f_2^2 C_2 - f_1^2 C_1} \tag{7}$$

Where C1 and C2 are calculated in terms of Colpitts capacitors $C_{c1}$ and $C_{c2}$ and $C_s$ as follows:

$$C_1 = \left( \frac{1}{C_{C1}} + \frac{1}{C_{C2}} + \frac{1}{C_S} \right)^{-1} + C_O \tag{7a}$$

$$C_2 = \left( \frac{1}{C_{C1}} + \frac{1}{C_{C2}} \right)^{-1} + C_O \tag{7b}$$

And $f_1$ and $f_2$ are the frequencies with $C_s$ in and out of the circuit, respectively. $L_m$ is then calculated from equation (6).

#2a – Chris Trask circuit & method

A variation on the shifted frequency method is the Chris Trask (N7ZWY) method and circuit that he published to the web in February, 2008. His circuit is designed to have the crystal oscillate on its actual series resonant frequency, eliminating approximations associated with the G3UUR circuit. It is somewhat more complex in that it incorporates AGC to keep the oscillator waveform sinusoidal. It also provides for an RF voltage drop measurement directly across the crystal for use in calculating $R_S$.

## Required test equipment for crystal measurements

<u>Bandwidth / Q measurement technique:</u>

1) A signal generator, stable and accurate to 1 Hz with known source resistance. (Source resistance can be assured with resistive pads.) The output should also be a clean sine wave, free of harmonics. Incorporate low pass filtering if necessary.
   a) A VXO, such as K8IQY's PVXO circuit
   b) A DDS synthesizer, such as an NJQRP unit
   c) A PLL/VCO oscillator, such at the MultiPig VFO

2) A frequency counter, unless a DDS is used
3) A detector. This is a means of measuring relative RF voltage or power into a known load resistance, usually 50 ohms. Absolute accuracy is not required because a 3 dB pad is used to determine the -3 dB points.
    a) A simple diode type detector and DMM is sufficient if drive level is high enough
    b) For lower levels, an amplified & compensated type diode detector, such as the NORTEX Accuprobe might be used
    c) A log RF power meter such as kitted by Kanga is suitable although more sophisticated than needed for this application
    d) An oscilloscope is another option for the detector
4) A switchable 3 dB resistive attenuator. Easily built with three resistors and a toggle switch.
5) A small value non-inductive potentiometer and an ohmmeter

G3UUR Method (measures Lm and Cm but not Rs)

1) A simple (two transistor) crystal oscillator circuit with crystal socket
2) A frequency counter accurate to 1 Hz

Chris Trask (N7ZWY) Method

1) Measurement circuit published by N7ZWY
2) Frequency counter accurate to 1 Hz
3) Oscilloscope or RF voltmeter (needed for Rs measurement only)

With any of the methods used, measurement of Co is performed using a capacitance meter accurate to 0.1pF such as the AADE or Elsie circuits. Co may also be estimated to good accuracy with no measurement needed.

**Quotes, facts, tips, opinions & one-liners about crystals & crystal filters**

- Co (holder capacitance) is usually approximated by Co = $220C_m$, which is derived from the physics of an AT cut crystal. In practice add 0.5 to 1 pF to this value. (1) (2)
- Always ground the crystal case. (3) (Note that some authors state that they do not ground the case for fear of damage caused by soldering.)
- If the crystal case is grounded, reduce the measured Co by half the capacitance measured from both pins shorted together to the case. (3)
- Chebychev filters tear up the timed pulses of RTTY, AMTOR, or Clover signals. Two good choices for data modes are Gaussian-6-dB and Gaussian-to-12 dB designs.

- Filter bandwidth has been found to be inversely proportional to the square root of the coupling capacitance. (6)
- Wider filters operate at higher impedances and have smaller coupling capacitors. (7)
- Miniature, wire-ended crystals (e.g., HC49/U) require a higher circuit impedance than HC-6/U types. (6)
- A Chebyshev with 0.1 dB of ripple is the most commonly used response type for SSB HF filters. (9)
- The recommended frequency range for an SSB crystal filter is between 6 and 12 MHz. (9)
- There is no physical difference between a "parallel" and a "series" type crystal.
- Choose crystals with a maximum frequency spread of about 10% of your filter bandwidth
- From (15), the difference in the series and parallel resonant frequency of a crystal can be approximately fairly closely with this formula:

  $$\Delta f \cong \frac{f \times C_m}{2C_o}$$

  Where f is the nominal frequency of the crystal, Cm is the motional capacitance and Co is the holder capacitance.
- From (16) (AADE quoting Hayward), the normalized Q of the filter must be greater than twice the number of crystals in the filter, or
  2 * # of crystals < Qu * BW / f where
  Qu is the unloaded Q of the crystals, BW is filter bandwidth and f is the crystal frequency

## References

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