Crystal Parameter Measurement and Ladder Crystal-Filter Design

A crystal text fixture, procedures and a spreadsheet smooth this traditionally complicated process.

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When designing crystal filters or crystal oscillators, it is essential to accurately measure the parameters of the crystals used if results are to agree with the design calculations. While a number of articles have been written to describe measurement techniques, most require several measurements and numerous calculations to obtain the crystal parameters.[1-5] Since many crystals often need to be measured to select those crystals that have the necessary parameters, the entire process can be very unwieldy and time consuming. The goal of this article is to simplify that task. I present two measurement techniques from which the reader can select one based upon available test equipment. With the measurements done, we can use *Excel* spreadsheets to ease the calculations. Last, a spreadsheet based upon a previous article in *QST* (see Note 3) is presented for taking measured crystal parameters and designing simple ladder crystal filters.

[1]Notes appear on page 42.

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Tutorial

To understand how the crystal parameters are measured, let's have a short tutorial on crystal models. The typical four-element crystal model is shown in Fig 1 (more complex models have been developed, but they are not needed for most applications). The crystal model consists of a series of lumped elements (inductor L_m, a capacitor C_m, and a series resistance R_s) in parallel with capacitor C_o. L_m and C_m represent the "motional" inductance and capacitance of the crystal and R_s represents the series resistance of the crystal. C_o represents the shunt holder capacitance of the crystal.

The transmission response of a crystal is shown in Fig 2. This is based upon a simple test setup shown in Fig 3. The crystal has a very low resistive impedance equal to R_s at the series-resonant frequency because the inductor and capacitance impedances cancel at this frequency, leaving only the series resistance, R_s . Therefore, the transmission signal output amplitude is maximum at the series-resonance frequency because this is the lowest series impedance possible. The series-resonance frequency is given by:

$$F_s = \frac{1}{2\pi\sqrt{L_m C_m}} \qquad \text{(Eq 1)}$$

The parallel resonance frequency is a function of C_o and any stray capacitance (C_s) plus L_m. It presents high transmission impedance, hence the low output amplitude shown in Fig 3 for the parallel-resonance frequency. The parallel-resonant frequency is:

$$F_p = \frac{1}{2\pi\sqrt{\dfrac{L_m C_m (C_o + C_s)}{C_m + C_o + C_s}}} \qquad \text{(Eq 2)}$$

where C_s is the stray capacitance across the crystal's terminal leads. Notice that the parallel-resonance frequency is affected by the presence of stray capacitance.

This test setup will measure the series-resonance frequency correctly, but not the true crystal parallel-resonance frequency because of stray capacitance added by the simple test setup. Therefore, to accurately measure the true crystal parameters, it is necessary to cancel out the effects of the stray capacitance caused by the test fixture. This may be achieved by means of an anti-phase voltage through another capacitor equal to that from the stray capacitance as shown in Fig 4. Notice that both V_{in} voltage sources have the same magnitude but differ in phase by exactly 180°. They go through equal-value capacitors (C_{adj} is set to equal C_{stray}). Therefore the current through C_{stray} is exactly cancelled by the current through C_{adj}, and the net result is that the circuit behaves as if only L_m, C_m, R_s and C_o were present, thus canceling the effects of C_{stray}.

In terms of a practical circuit, the two opposite-phase voltage sources can be implemented with a transmission-line transformer, as shown in Fig 5. The 1:1 transformer is used to generate an anti-phase voltage for the neutralizing capacitor leg by inverting the polarity of the input voltage going into the crystal.

The input and output resistor pads lower the impedance of the source and load (to 19.1 Ω) as seen by the crystal to better match the series resistance of the crystal (typically in the 10-35 Ω range for most crystals in the 1-20 MHz range) for more accurate measurements.

Test Fixture Construction

The crystal measurement test fixture is based upon a Tektronix Application Note (see Note 1). It is relatively easy to build and its layout is not critical, as long as leads are kept short. I constructed my crystal-measuring test fixture in an aluminum case for shielding, using a die-cast enclosure made by LMB (model CAB-123). It is 3 3/8 × 1 1/2 × 1 1/16 inches (LWH). I used five-way

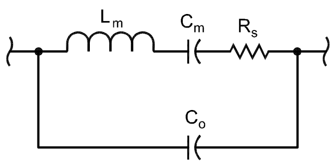

Fig 1—Lumped-element model of a crystal.

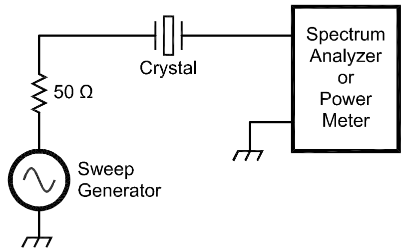

Fig 2—Crystal transmission response.

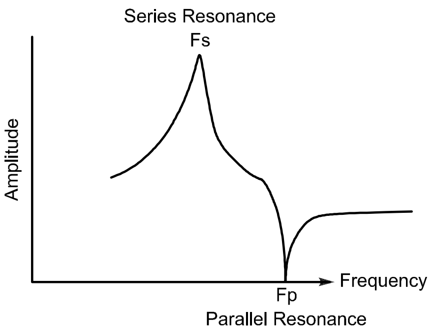

Fig 3—Simple crystal measurement test setup.

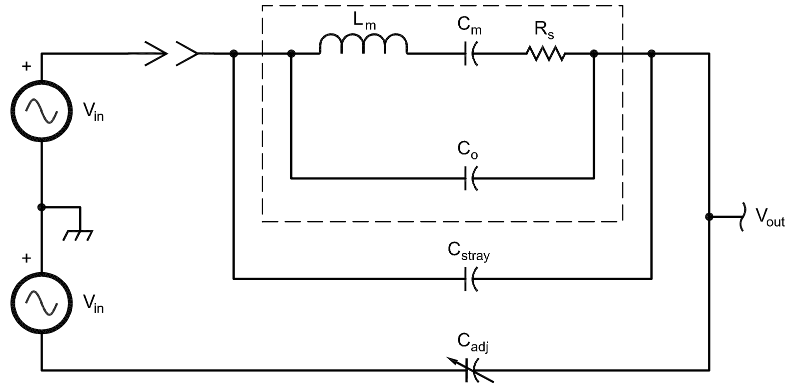

Fig 4—C_{stray} cancellation circuit.

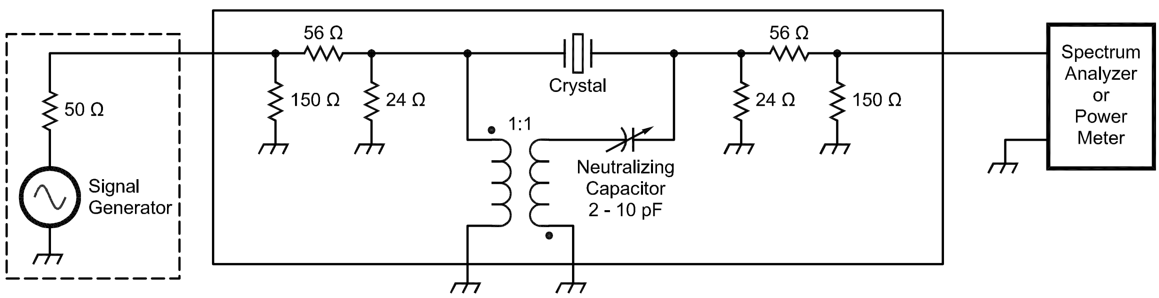

Fig 5—Crystal measurement test fixture.

terminal posts for the crystal connectors and BNC connectors for the signal input and output connectors. The 1:1 transformer was made with an Amidon FT37-43 toroid core, wound with two sets of windings, each consisting of 16 turns of #28 AWG wire, as shown in Fig 6. The neutralizing capacitor is a 2-10 pF piston capacitor, although any type should work. Make sure that it can be insulated from the chassis. A picture of the outside of the test fixture is shown in Fig 7 and a picture of the inside of the test fixture is shown in Fig 8.

Measurement Techniques

This article describes two alternative measurement techniques, with *Excel* spreadsheets to ease the calculation process. The first technique uses either a signal generator and power meter (or spectrum analyzer) or a scalar or vector network analyzer with the test fixture. A second technique uses a vector voltmeter for those individuals that have access to one. It does not require the test fixture. Regardless of the particular technique used, each will give accurate results using the *Excel* spreadsheets. The end result is a relatively painless technique to accurately characterize crystals.

The first approach only requires a signal source (CW signal generator or sweep generator) and a level measuring device (power meter or spectrum analyzer), as shown in Fig 5. The main requirement of the signal generator (or frequency counter) is that it can be set accurately in frequency and that it is stable during the measurement. That is ideally a setting accuracy to 1 Hz or better and drift of less than 1 Hz during the measurement. The power meter or spectrum analyzer needs to resolve levels to 0.1 dB or better. The absolute accuracy is not very important because only power differences (over a typical range of 2-4 dB for most crystals) are measured.

Table 1 gives a detailed measurement procedure using this method. Notice that the value of C_0 is extremely sensitive to the measured value of the parallel-resonant frequency, so take care that you measure the frequency of the minimum signal point corresponding to F_p. This is not always easy to do because the signal is often down in the noise where the true null is difficult to identify.

A vector RF impedance meter, such as the HP-4815A, can also be used for determining the parameters of a crystal. The technique is based upon the crystal-impedance characteristics as shown in Fig 9. The key characteristics of the crystal impedance are that

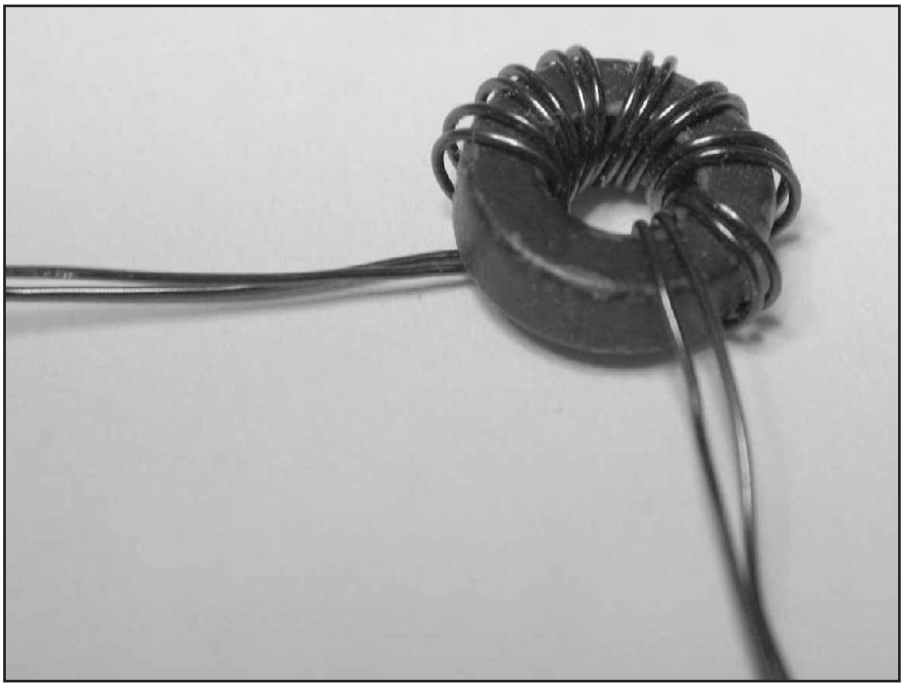

Fig 6—Construction of a 1:1 transformer.

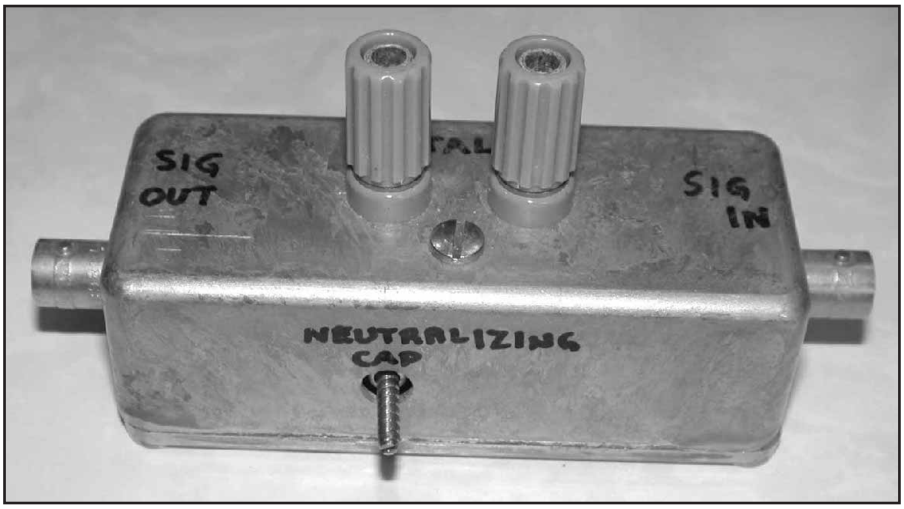

Fig 7—Outside view of crystal measuring test fixture.

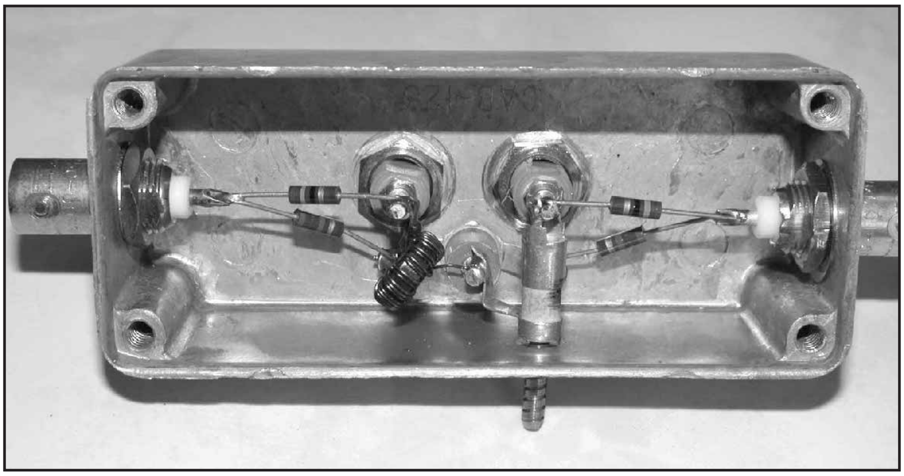

Fig 8—Inside view of crystal measuring test fixture.