What's this 30 pF Stuff? *

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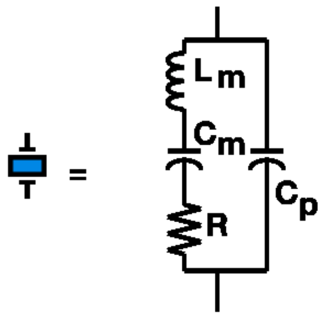
Quartz crystals are among the more interesting components that we study in our quest to understand analog electronics. A thin piece, usually a disc, has two attached wires. Visual examination shows it to be a disc of translucent material with metal plating, complete with attached wires. In short, it's a capacitor, but one with the useful property of behaving as if it was a series tuned LC circuit. Not only does this element have excellent temperature stability, but it has very low loss. The following figure shows the equivalent circuit. L_m and C_m have the subscript "m" to indicate that they are *motional* components, indicative of a mechanical motion within the crystal structure.



Crystal Model

The parameters include the motional inductance and capacitance, a loss resistance sometimes shown as ESR, or Equivalent Series Resistance, and a parallel capacitance, C_p. Sometimes the parallel capacitance is signified by C_0.

We recently purchased some 9 MHz crystals for use in bandpass filters. These parts were specified for a 30 pF load. What does this mean? This note is offered as an explanation. One of our crystals was measured and studied with a vector network analyzer. The VNA was one of the N2PK instruments. The VNA output was attenuated with a 6 dB pad and then applied to a 6 dB hybrid, a.k.a. return loss bridge. The system was calibrated with the usual OSL (open, short, load) system. A program, "xtal2.exe" written by N2PK was used with the instrument, The VNA provided the following data:

$$f_s = 8.99715\times10^6, L_m = 0.015582, C_p = 4.85\cdot10^{-12}$$

The series frequency, f_s, is about 3 kHz below the specified 9.000 MHz resonant frequency. The motional inductance is 15.56 millihenry while the parallel capacitance is almost 5 pF. These results are typical of the crystals in this Mouser order. The series frequency is converted to an angular frequency, Omega, with the usual formula:

$$\omega_s = 2\pi f_s$$

This form is then used with L_m to calculate the motional capacitance, C_m, from the resonance equation.

$$C_m = \frac{1}{\omega_s^2 L_m}$$

$$C_m = 2.0082e\text{-}14$$

These motional values, L_m and C_m, are totally foreign to any intuition we might have regarding LC components in the HF spectrum. One femtofarad is 10^{-15} farad, so the motional capacitance is just over 20 fF, or .02 pF. L_m has a value expected in an audio circuit. The R value is a few ohms, corresponding to a Q value of 128,000.

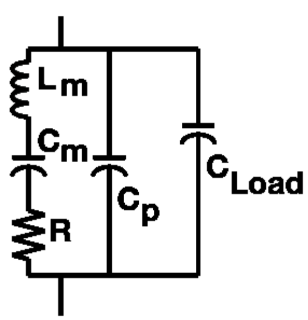
At the series resonant frequency, the impedance between the leads is very low, for the reactance of the motional L and C cancel. Besides series resonance, the parallel capacitance, C_p, generates a parallel resonance, a frequency where the impedance is very high. This is the frequency where L_m resonates with the series combination of C_m and C_p. Calculating f_p begins with a calculation of the series capacitance, C_{ser}.

$$C_{ser} = \frac{(C_m C_p)}{C_m + C_p}, \quad f_p = \frac{1}{2\pi\sqrt{L_m C_{ser}}}$$

$$f_p = 9.01575e{+}06$$

f_p is the parallel resonant frequency for this crystal. It occurs at nearly 16 kHz above 9 MHz, or 19 kHz above the series resonance.

IQD, the manufacturer of this crystal, has specified the resonant frequency as 9 MHz with a 30 pF load. The meaning of this is illustrated in the next figure.



Crystal with External Load Capacitance

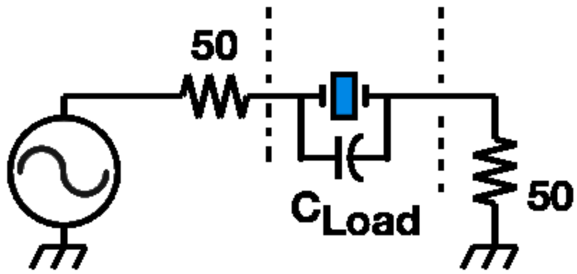
This represents a crystal that is loaded with additional capacitance, C_{Load}. This might be the capacitance of a transistor and related components when the crystal is used in an oscillator. The resonant frequency for the above circuit is calculated when we evaluate L_m with a net capacitance of the parallel combination of C_p and C_{Load} in series with C_m. We signify the net capacitance as C_x, resulting in a resonant frequency f_x.

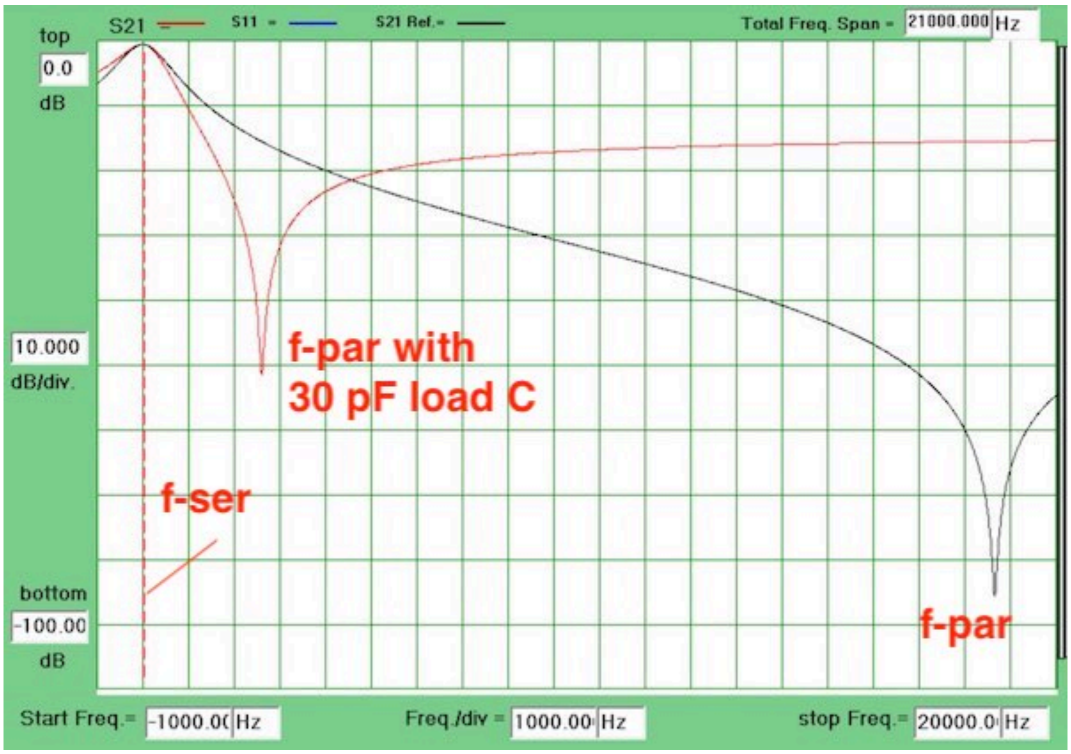
$$C_x = \frac{(C_m (C_p + C_L))}{C_m + (C_p + C_L)}, f_x = \frac{1}{2\pi\sqrt{L_m C_x}}$$

$$f_x = 8.99974e+06$$

This resonant frequency is only 240 Hz below 9.000 MHz. It is a specification detail that has little to do with most applications. It might have been significant in earlier times when oscillator circuits were so characterized. It was common for crystal manufacturers to maintain a database of equipment, allowing someone to specify that equipment when they requested a crystal that would operate at a desired frequency. But that was an earlier time.

The following figure shows a crystal, including a load capacitance, embedded in a VNA. The load may or may not be present.





The graph shows the measurement results. The series frequency is show at 0 Hz in this plot with the parallel resonance 18.6 kHz higher. This plot is in black with C_{Load}=0. The red plot shows the VNA response if the load is increased to 30 pF.

A crystal specified to have a stated load C will oscillate at the marked frequency when that load is present. This frequency will always be between the series and the parallel resonant frequencies.

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* If the title of this piece seems slightly familiar, it's because the form is that popularized in the Electrical Engineering trade literature in the 1980s and 1990s by Bob Pease. He was a designer of analog circuits, primarily for National Semiconductor. It was rare to see a copy of EDN that didn't have one of his "What's this ______ Stuff?" articles. We all miss his sometimes caustic, but always insightful take on circuits.