Negative Resistance Measurement

Traditionally most design engineers believed that the oscillation allowance (|–R|/RL) of 5 to 10 has been good enough for most crystal oscillator circuit. In fact it was only a reference figure for some consumer products but obviously never be the guidance for tough reliability requirements such as in automotive industry. There are many consideration factors such as the target quality level, the characteristics of the oscillation circuit (e.g. AGC, sleep mode, drive power…), the crystal package size, the operating frequency and etc. Evidences have proven that the negative resistance required is much higher than that traditional engineers thought. For reliable startup, –R of -300 to -2000 Ohm is required for high frequency fundamental crystal, and -1200 to -4000 Ohm for medium and low frequency. The negative resistance of the circuit must be carefully measured and adjusted before putting the product into mass production. A practical measurement method for –R is introduced in this application note.

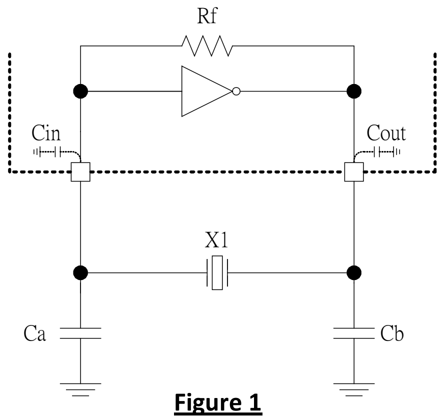

Figure 1

One of the most commonly used crystal oscillation circuit nowadays is Pierce-gate as shown in figure 1. It comprises a simple inverter gate, a feedback resistor Rf, two external load capacitors Ca and Cb, and a crystal X1.

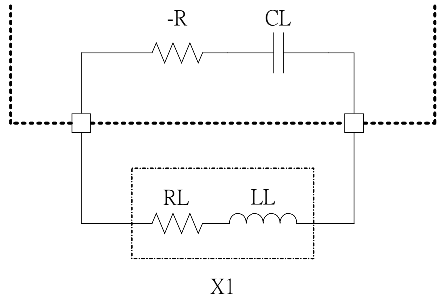

Figure 2

The equivalent circuit is shown in figure 2. At resonance, the crystal becomes a resistance RL in series with an inductance LL. The gate amplifier and its associated components form a negative resistance –R in series with a load capacitance CL.

The equivalent negative resistance (-R) can be estimated by a simplified equation:

$$-R = -\frac{gm}{\omega^2 \cdot (Ca+Cin) \cdot (Cb+Cout)} \qquad (1)$$

where:

$\omega = 2\pi f$
gm = transconductance of the gate amplifier
Ca, Cb = external load capacitance
Cin, Cout = input and output pin stray capacitance

The above equation is a simplified model with certain assumptions, and it should be used for rough estimation only. A more precise model would include additional parasitic and C0 of the crystal as well.

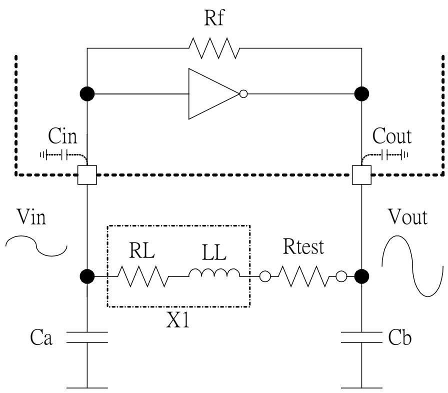

Figure 3

A more practical way for negative resistance measurement is shown in figure 3. An add-on resistor Rtest (low inductance preferred) is connected in series with the crystal as in figure 4. Rtest would be replaced by higher resistance value step by step until oscillation stopped. Oscillation voltages could be measured at the amplifier output (Vout) by oscilloscope with low capacitance probe (e.g. FET active probe). Measuring at the amplifier input should be avoided due to the loading effect of the probe and the high input impedance of the amplifier. The total resistance of Rtest and crystal RL equals to the negative resistance of the oscillator.

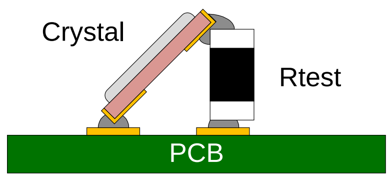

Figure 4

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The negative resistance can be expressed by:

$$|-R| = \text{Rtest} + \text{RL} \quad (2)$$

since,

$$\text{RL} = \text{Rs}\left(1 + \frac{\text{C0}}{\text{CL}}\right)^2 \quad (3)$$

Put (3) into (2), then,

$$|-R| = \text{Rtest} + \text{Rs}\left(1 + \frac{\text{C0}}{\text{CL}}\right)^2 \quad (4)$$

where:

Rtest = maximum value of add-on resistance at which oscillation can still be maintained
Rs = Equivalent resistance of the crystal at series resonance
RL = Equivalent resistance of the crystal at load resonance
C0 = Shunt capacitance of the crystal
CL = Equivalent load capacitance of the oscillation circuit

The crystal parameters C0 and Rs could be measured with a crystal network analyzer such as KOLINKER KH1800, or with measurement method complies with IEC60444-5 and -11 international standards.

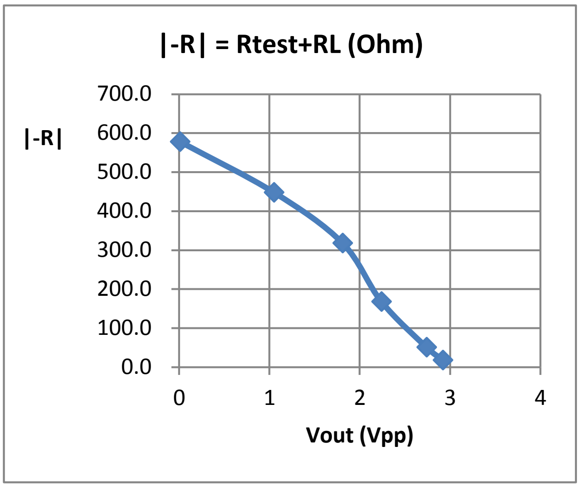
Example:

The parameters of a 27MHz crystal in an oscillator are:

FL [Hz]	Rs [ohm]	RL [ohm]	CL [pF]	C0 [pF]	Ts [ppm/pF]
27000000	10	17.9	6.5	2.2	57

According to the setup in figure (3), the following results were measured:

Rtest (Ohm)	Rtest+RL (Ohm)	Vout (Vpp)
0	17.9	2.92
33	50.9	2.74
150	167.9	2.24
300	317.9	1.81
430	447.9	1.05
560	577.9	0.01



In this example, the negative resistance (-R) is -577.9 Ohm.

The minimum negative resistance required by a product highly depends on the target quality level, the operating frequency, the crystal package size and the end application. And the data could be obtained from the crystal manufacturer. In case the –R is insufficient for achieving a target quality level, it can be improved by reducing the external load capacitance Ca and Cb in most cases. And of course new matching for CL and drive power has to be done again. Frequency error budget should also be reviewed.

For more information about load capacitance and drive level measurement, please refer to application note ANENG-XTL-0012 and 0013, or consult the crystal manufacturer.

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