Oscillator Circuit Evaluation Method (1)

Steps for evaluating oscillator circuits (frequency matching)

Preface

In general, a crystal unit needs to be matched with an oscillator circuit in order to obtain a stable oscillation. A poor matching between the crystal and an oscillator circuit can produce a number of problems, including, insufficient device frequency stability, devices stop oscillating, and oscillation instability. Thus, Oscillator circuits need to be evaluated when a crystal unit is used in combination with a microcontroller. To check the matching between a crystal unit and an oscillator circuit, you must evaluate at least the oscillation frequency matching, negative resistance, and drive level. This paper describes the evaluation process used to check the matching of a crystal unit and an oscillator circuit.

1. Preparations for oscillation frequency matching evaluations

A circuit designer basically specifies three crystal unit parameters: load resonance frequency (F_L), load capacitance (C_L), and crystal frequency tolerance (delta f). Given these parameters, the crystal manufacturer vibrates the crystal unit in accordance with the load capacitance (C_L) as it adjusts the load resonance frequency (F_L) and frequency tolerance.
However, the pre-specified load capacitance (C_L) gives no consideration to electrostatic capacitance (stray capacitance), which is produced by a variety of sources on the printed circuit boards (PCBs). Since stray capacitance adversely affects accuracy of the oscillation frequency, it has to be offset either by the crystal manufacturer, who can change the frequency of the crystal unit itself, or by the circuit designer, who can adjust the load capacitance. This process is called frequency matching.

Before you evaluate the frequency matching, you need to confirm the following three specifications for the crystal unit to be evaluated.

1. Standard load capacitance
   From a crystal unit perspective, load capacitance is the electrostatic capacitance of the oscillator circuit. Normally, the circuit designer specifies the load capacitance.
2. Load resonance frequency of the crystal unit with the standard load capacitance
   Load resonance frequency (F_L) is the oscillation frequency when a crystal unit is driven with an oscillator circuit that has the standard load capacitance. The value at room temperature is used. Stray capacitance and other factors are not taken into account.
3. Equivalent circuit constants for a crystal unit
   The main constants are motional resistance (R_1), motional capacitance (C_1), motional inductance (L_1), shunt capacitance (C_0), and the resonance frequency (Fr) of the crystal itself, without taking load capacitance into account.
   Impedance meter and network analyzer are generally used to measure the parameters of the equivalent circuit for a crystal unit. Ideally, the circuit designer should measure the crystal unit with a network analyzer and measure the equivalent circuit parameters. However, if the circuit designer lacks the equipment or expertise required to measure the crystal unit, he or she should ask the crystal manufacturer to do so.

2. Oscillation frequency matching evaluations

From here we begin the actual evaluation process.
First, mount the crystal unit to be evaluated on a PCB along with the oscillation circuit, and check the

crystal's oscillation frequency. This is often referred to frequency matching check.
Determining the difference between the oscillation frequency, when the crystal is mounted on the PCB and the oscillation frequency at the standard load capacitance, enables you to see the difference between the actual electrostatic capacitance (circuit-side capacitance) of the PCB and the pre-specified standard electrostatic capacitance. The electrostatic capacitance of the PCB consists not only of the electrostatic capacitance (load capacitance) of the oscillation circuit from a crystal unit perspective, but also includes the stray capacitance that arises from sources such as the wiring pattern of the board.

Next, prepare the measuring instruments you need to evaluate the match between the crystal unit and the oscillation circuit. The basic measuring instruments you need to evaluate the match between frequencies are a direct current power supply, frequency counter, oscilloscope, FET probe, and current probe. (Fig. 1 provides an example of a basic measuring instrument configuration.)

Fig. 1: Measuring instruments for evaluating frequency matching

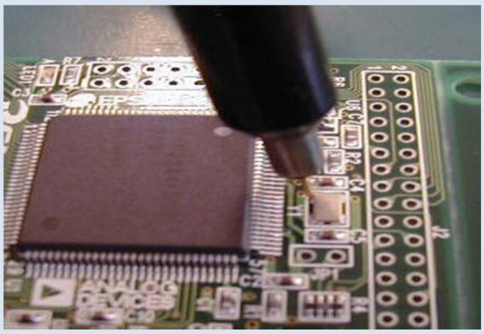


Fig. 2: Touching the hot terminal of the crystal unit with the FET probe to check the oscillation waveform

First, when you touch the hot terminal of the crystal unit with the FET probe (Fig. 2), a waveform appears on the oscilloscope and the frequency is displayed on the frequency counter.
Let's assume, for example, that we have a crystal unit whose resonance frequency (Fr) without load capacitance is 12 MHz. Let's now assume that the load resonance frequency (F_L) of the crystal with the standard load capacitance is 12.000034 MHz.
Now, let's assume that the oscillation frequency of the crystal unit when mounted on the PCB (F_R) was measured using a FET probe and found to be 12.000219 MHz, meaning that the difference between the two [the oscillation frequency when the crystal is mounted on the board (F_R) and the oscillation frequency with the standard load capacitance (F_L)] is +185 Hz, a difference of +15.4 ppm.
Bringing the difference between these two frequencies to as close to zero as possible improves frequency accuracy.
There are two ways to reduce the difference between F_R and F_L.
One way is to order crystal units whose oscillation frequency (center frequency) is +15.4 ppm higher than before. The other way is to fine-tune the load capacitance of the oscillation circuit so that it matches the oscillation frequency.
The procedure for fine-turning and matching load capacitance with the oscillation frequency is described below.

3. Matching frequencies by fine-tuning load capacitance

You need to know the following values to calculate load capacitance:

- The equivalent circuit constants of the crystal (Fr, R_1, C_1, L_1, and C_0)
- The oscillation frequency when the crystal is mounted on a PCB (F_R)

Calculate load capacitance (C_L) by plugging the foregoing values into the formula below.

$$\frac{F_R - Fr}{Fr} = \frac{C_1}{2 \times (C_L + C_0)} \quad \ldots \quad Formula(1)$$

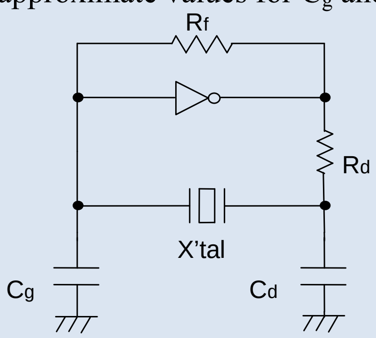
Here is a specific example of a calculation.
Let's assume that you have a crystal that has a nominal frequency of 12 MHz and an oscillation circuit load capacitance (C_L) of 7.8 pF. The nominal frequency is the oscillation frequency (F_L) when an oscillation circuit having the specified load capacitance is used.

The crystal's constants, as measured by a network analyzer, were as follows:

F_R=12.000219 MHz , Fr＝11.998398 MHz

R_1＝33.7 ohm , L_1＝70.519 mH , C_1=2.495 fF , C_0=1.11 pF

Remember, Fr is the resonance frequency of the crystal. When you plug these constants into the formula, you will find that C_L = 7.11 pF.
The difference between this value and the specified 7.8 pF oscillation circuit load capacitance (C_L) is -0.69 pF. If this difference is eliminated, the load capacitance of the pre-specified oscillation circuit and the electrostatic capacitance of the crystal unit when it is actually mounted on a PCB will match. Theoretically, the frequency deviation will also be zero, yielding to the pre-specified oscillation frequency.
When you actually adjust the load capacitance of the oscillator circuit, change C_g and C_d (Fig. 3) so that it matches the pre-specified standard electrostatic capacitance. You can use Formula 2 below to calculate the approximate values for C_g and C_d.



$$C_i = \frac{C_g \times C_d}{C_g + C_d} + C_s \quad \ldots \quad \textit{Formula}(2)$$

Fig. 3: Circuit load capacitance (Cg & Cd)

C_i represents the actual load capacitance (C_L) of the oscillation circuit, and C_s represents capacitances such as PCB wiring capacitance and the parasitic capacitance of components. Since C_i needs to match the pre-specified standard electrostatic capacitance C_L (the C_L of the standalone crystal unit).You can calculate it using Formula 3 and Formula 4 below.

$$\frac{C_g \times C_d}{C_g + C_d} + C_S = C_L \quad \ldots \quad \textit{Formula}(3)$$

$$\frac{C_g \times C_d}{C_g + C_d} = C_L - C_S \ldots \quad \textit{Formula}(4)$$

In other words, C_g and C_d are the prescribed crystal unit load capacitance from which C_s is subtracted. This value is nothing more than approximations, it is recommend that you change C_g and C_d and check the oscillation frequency as you perform adjustments to obtain the desired frequency.
If changing the oscillation circuit's C_g and C_d is difficult, you can obtain the desired frequency by adjusting the load capacitance of the standalone crystal unit. In this case, ask the crystal manufacturer to match the standalone capacitance of the crystal unit to the circuit capacitance, then evaluate the match and check the results. However, be aware that the oscillation frequency is subject to large changes if the circuit load capacitance is small, making it susceptible to even very slight changes in characteristics of the oscillator circuit, causing the frequency stability to deteriorate. For this reason, it is important to set suitable parameters in accordance with the application of the device. *(To be continued…)*