Rockwell

R6500 Microcomputer System
APPLICATION NOTE

Crystal Considerations for 6500 Family Devices

INTRODUCTION

Since a quartz crystal is commonly used as a frequency control element in microprocessor applications, design engineers are often faced with the task of specifying crystal parameters.

This application note is intended to answer questions on crystal specifications and the oscillator circuits used in the various Rockwell microprocessor family components. A brief explanation of crystal characteristics is followed by a discussion of oscillator basics and equations relating crystal parameters with amplifier characteristics. This note also includes a list of suggested crystal specifications, several suppliers and vendor part numbers.

BASIC CRYSTAL CHARACTERISTICS

Crystal Equivalent Circuit

Quartz crystals are piezoelectric devices that transform electrical energy into mechanical vibrations, which in turn cause voltage oscillations. The frequency of the crystal depends mostly on its size, with smaller and thinner crystals producing a higher frequency.

A crystal has the equivalent electrical circuit shown in Figure 1.

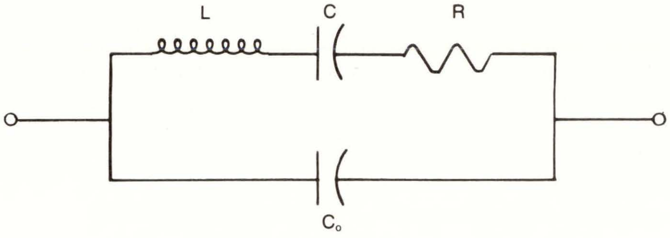

Figure 1. Electrical Equivalent Circuit of Crystal

The L, C, R branch is known as the motional arm. The parameters L, C, and R are referred to as the electrical equivalent of the mechanical parameters inertia, restoring force, and friction, respectively.

C_o represents the shunt capacitance between the terminals of the crystal and is the sum of the crystal electrode capacitance and package capacitance due to wire leads and the crystal holder.

Although crystals are generally specified as series or parallel resonant, typically a crystal is only labeled with its frequency, with no indication whether the frequency was calibrated for series or parallel mode oscillator operation. A crystal used as a series resonant circuit has an output in phase with its input, while a crystal used as parallel resonant will cause a phase shift from its input to the output.

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Since a crystal is effectively a tuned circuit, the reactance of this circuit can be calculated and plotted against frequency, as shown in Figure 2.

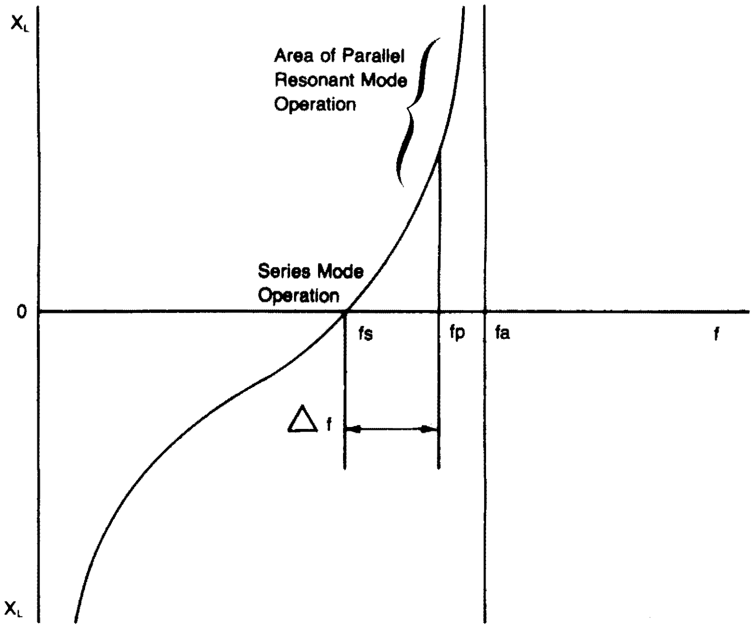

Figure 2. Reactance vs. Frequency Plot of Crystal

This reactance vs. frequency curve illustrates the two different operating regions. At series resonance, fs, the reactance of the equivalent circuit becomes zero and the crystal appears resistive in the circuit (Figure 3a). In this mode, correlating frequency to load capacitance is not a problem. However, the maximum equivalent series resistance (Rs) must be specified. The equivalent series resistance directly affects the loop gain, as will be shown later. If the load capacitance is not specified when ordering, crystals will be calibrated at series resonance.

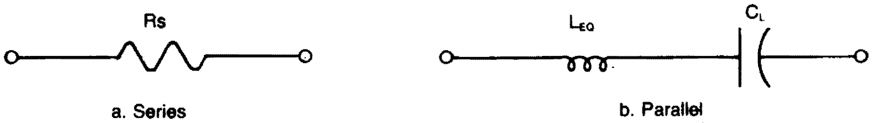

Figure 3. Crystal in Series and Parallel Mode

The crystal operating at parallel resonance (Anti-resonance) appears inductive in the circuit (Figure 3b), and any changes in circuit reactance values will affect the crystal frequency. Therefore, if the crystal is to be used at parallel resonance, the load capacitance, C_L, should always be specified. The load capacitance is the dynamic capacitance of the total circuit, measured across the crystal terminals. The difference between f_p and f_s is very small—typically 425 ppm. (See Figure 2).

OSCILLATOR BASICS

Barkhausen Criteria

In its simplest form, an oscillator is an amplifier whose output is fed back to its input through a frequency sensitive network. Figure 4 shows a block diagram of such a circuit.

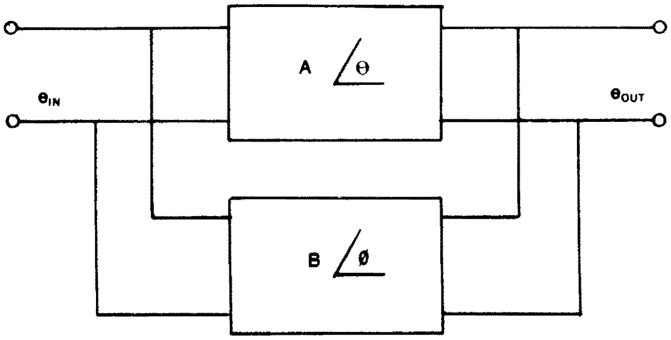

Figure 4. Block Diagram of Basic Oscillator

The amplifier has a gain of magnitude A with a phase shift of Θ at the frequency of oscillation, ω_o. The frequency sensitive network has a gain of magnitude B, usually less than unity, and a phase shift of Θ at ω_o. Barkhausen's criteria states that for oscillation to occur, the product of the gain around the loop must be equal to or greater than unity, and that the sum of the phase shifts around the loop must equal n × 360° at the frequency of operation, ω_o. Equations 1 and 2 state the Barkhausen criteria as it is applied to the above simple oscillator.

$$A \cdot B \geqslant 1 \tag{1}$$

$$\Theta + \emptyset = n \cdot 360^\circ \tag{2}$$

Where $n = 0, 1, 2, 3 \ldots$

For the purpose of analysis, the basic oscillator block diagram is redrawn with the loop open, and the phase shift network terminated in the amplifier input impedance, as shown in Figure 5.

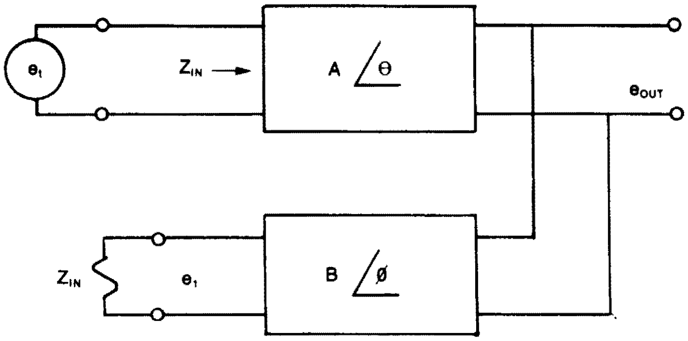

Figure 5. Oscillator with Loop Open

The relationship between e_t and e_1 can be expressed as

$$e_1 = e_t \cdot A \angle \theta \cdot B \angle \emptyset \quad \text{or} \quad \frac{e_1}{e_t} = A \cdot B \angle \theta + \emptyset$$

For oscillation to occur $A \cdot B \geqslant 1$ and $\theta + \emptyset = n \cdot 360^\circ$ at ω_o.

Crystal Oscillator Analysis

Consider the typical crystal oscillator circuit shown in Figure 6, which uses a FET as an active device. This is a simplified version of the FET amplifier in the R6500/1 microcomputer oscillator circuit.

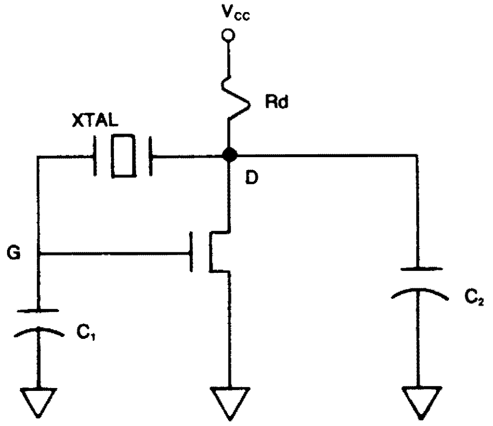

Figure 6. Simplified Oscillator Circuit

The impedance of C_1, C_2 and the crystal make up a π network, and its equivalent circuit would appear as shown in Figure 7.

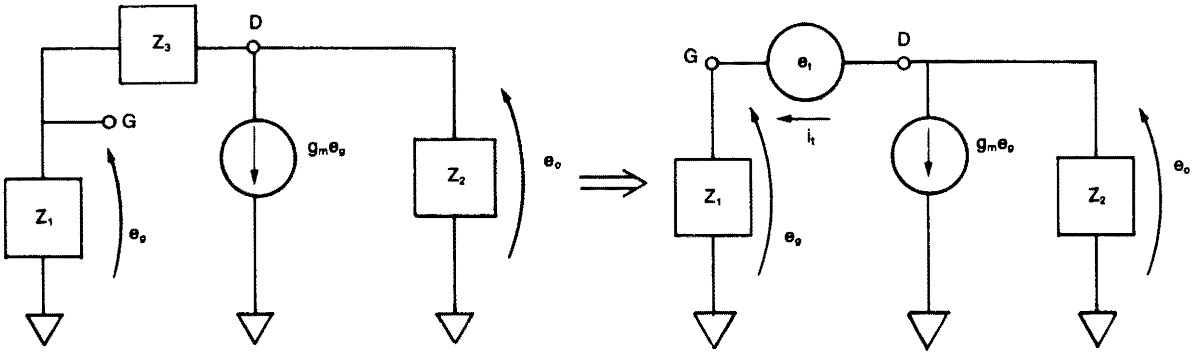

Figure 7. Hybrid-π Equivalent Circuit

R_d is assumed to be much larger than Z_2 for the purpose of illustration and keeping the equations simple. We wish to determine the impedance looking into terminals G and D with Z_3 removed

$$e_t = i_tZ_1 + i_tZ_2 + g_me_gZ_2 \qquad (1)$$

Substituting $e_g = i_tZ_1$ into (1)

$$e_t = i_tZ_1 + i_tZ_2 + g_mi_tZ_1Z_2 \qquad (2)$$

$$Z_{GD} = \frac{e_t}{i_t} = Z_1 + Z_2 + g_mZ_1Z_2 \qquad (3)$$

Substituting $Z_1 = \frac{1}{jwc_1}$ and $Z_2 = \frac{1}{jwc_2}$ into equation 3, we get

$$Z_{GD} = -\frac{g_m}{\omega^2C_1C_2} - j\left(\frac{1}{\omega C_1} + \frac{1}{\omega C_2}\right) \qquad (4)$$

The imaginary part represents C_1 and C_2 in series and the real part represents the magnitude of a negative resistance. Reinserting Z_3 (crystal) between the gate (G) and drain (D), we will have the equivalent circuit shown in Figure 8.

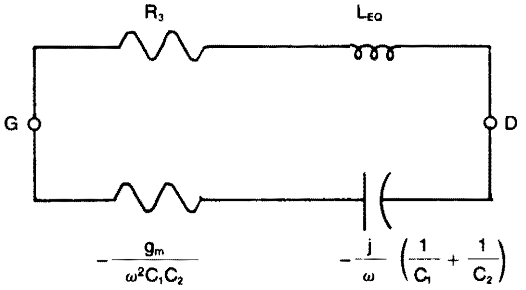

Figure 8. Oscillator Equivalent Circuit

If the negative resistance $\frac{g_m}{\omega^2C_1C_2}$ is greater than the losses of the feedback circuit elements, R_3, the system will oscillate at a frequency that makes the reactive terms zero. (Barkhausen Criteria)

That is

$$\omega L_{eq} = \frac{1}{\omega}\left(\frac{1}{C_1} + \frac{1}{C_2}\right) = \frac{1}{\omega}\left(\frac{1}{C_L}\right)$$

$$\omega^2 = \frac{1}{L_{eq}C_L} \quad \text{or} \quad \omega = \frac{1}{L_{eq}C_L} \quad \text{Where } C_L = \text{Load Capacitance}$$

The above equations are based on a simplified oscillator circuit. Although expressions for the actual oscillator circuit in the R6500/1 microcomputer device are much more complex, the same procedures would apply.

Oscillator Circuit for R650X Series Microprocessor

Figure 9 shows a series oscillator circuit recommended for use with R650X series microprocessors. The oscillator consists of two common TTL inverters, three resistors, and a crystal.

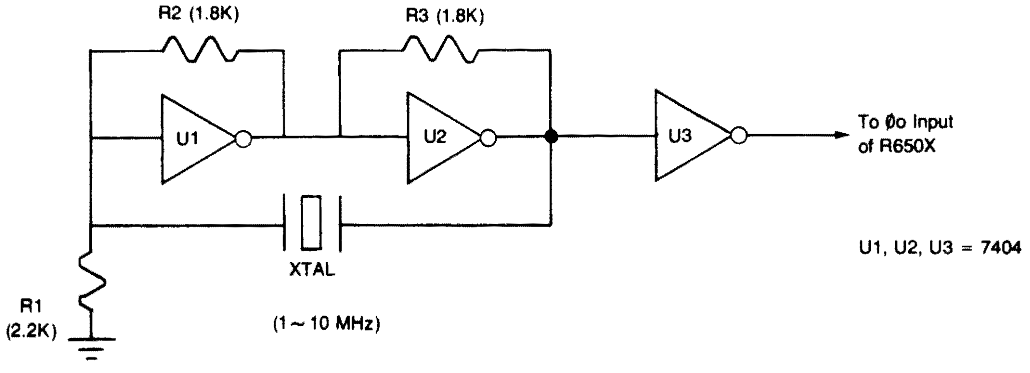

Figure 9. Oscillator for R650X Series

Inverting buffer U3 is optional, and the output of U2 may be used directly to drive the Ø0 input without affecting the oscillator performance. When U3 is eliminated or a non-inverting type buffer is used instead of an inverting type, the R1 value should be changed to 3.3KΩ. This will provide a proper adjustment to the Ø0 duty cycle.

The crystal controlled oscillator circuit suggested in earlier data sheets tends to generate a non-symmetrical clock signal. This non-symmetry can be improved up to 30% (Figure 10b) by replacing one of the clamping diodes with IN4003 diode (Figure 10a).

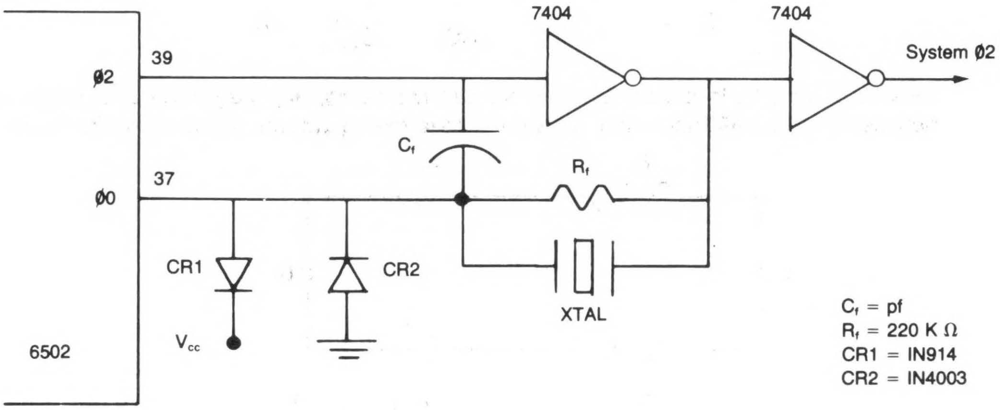

Figure 10a. Crystal Controlled Oscillator

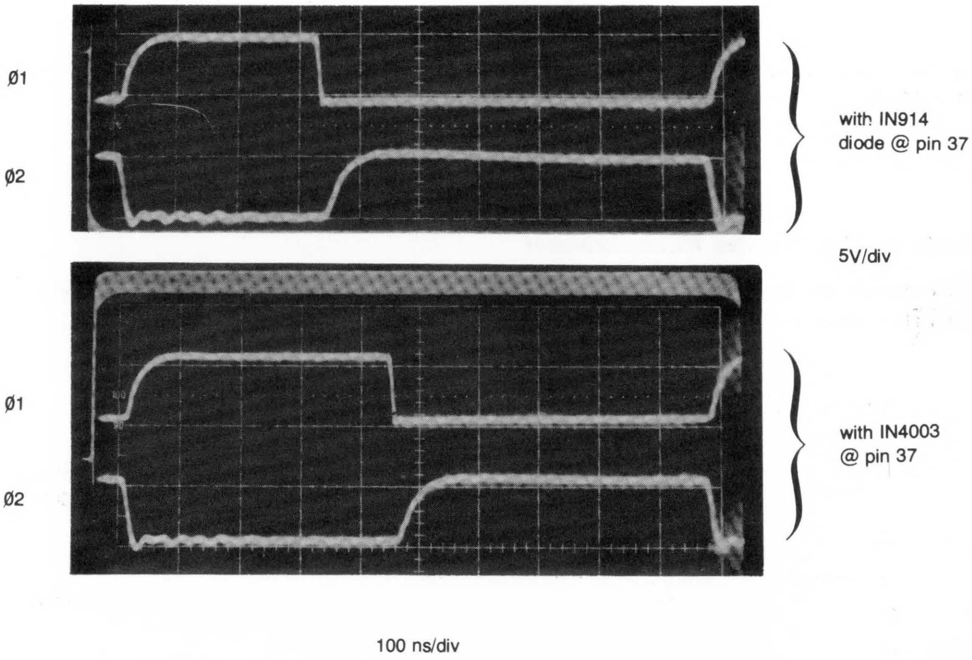

Figure 10b. Ø1 & Ø2 Clock Wave Forms

CRYSTAL SPECIFICATIONS

Most crystal manufacturers provide a specification form, and there is a tendency to fill in all the blanks provided on the form. Only the blanks for the parameters directly related to the performance of the crystal in the circuit should be filled in. Following is a list of suggested specifications for crystals to be used in most clock oscillator applications.

1. Frequency ______________MHz
2. Holder Type ______________
3. Frequency Tolerance ______________% @ ______________°C
4. Calibration—Series/Parallel (Circle One)
5. Load Capacitance ______________pf (parallel only)
6. Maximum Series Resistance ______________ohms
7. Drive Level ______________mw

Typically, frequency tolerance of crystals used in clock oscillator applications is ±50ppm or +0.005% or less. It is up to the user to specify holder types. Standard popular holders such as HC33/U (0.75"W#X#0.765"H, 1.5" lead length with 0.486" lead spacing) for frequencies up to 4 MHz and HC18/U (0.435"W#X#0.530"H, 1.5" lead length with 0.192" spacing) for frequencies higher than 4 MHz will satisfy most microprocessor applications. Drive level is defined as the amount of power dissipated by the crystal in the circuit. Typical drive levels range from 2 to 5 mW for frequencies up to 10 MHz. Excessive drive levels exerted on the crystal may cause frequency drift or fractures of the crystal. Crystal specifications for R6500 series components are tabulated in Table 1.

TABLE 1

Parameters/ Devices	Freq. MHz	Parallel/ Series	Load Cap (pf)	Series R Max. (ohms)	Suppliers CTS Knights	 Crystek
R6500/1	2 & 4	P	15	550	MPO 2 & 4	*
R6551	1.8432	S	N/A	650	MPO 18	*
R650X and TTL OSC.	1 & 2	S	N/A	1K	MPO 1 & 2	CY1A & 2A

*Contact vendor with the appropriate specifications.

Crystek
1000 Crystal Drive
Fort Meyers, Florida 33901

CTS Knights, Inc.
450 Reimann Avenue
Sandwich, Illinois 60548

Addresses of these two manufacturers are provided for convenience, and in no way implies that they are the only crystal suppliers available.

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