Application Report
SBAA123 – December 2004

# Using Crystal Oscillators with MSC12xx MicroSystem Products

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## ABSTRACT

Texas Instruments' MSC12xx data acquisition product line includes an enhanced 8051 microcontroller, a high-precision 24-bit delta-sigma (ΔΣ) analog-to-digital converter (ADC) and digital-to-analog converters (DACs). Also included is an onboard inverting amplifier that can be interfaced with a quartz resonator and other components for generating clock signals. This application report includes general information about crystal oscillators and their limitations due to component tolerance, temperature and voltage variations. Methods for enhancing performance and reliability are included along with specific guidelines for using crystal oscillators with the MSC12xx family.

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## 1 Introduction

Crystal oscillators are used in a variety of applications where clock signals are required. Microcontroller and data converter circuits that operate within specific frequency ranges make use of these simple yet sometimes frustrating cells. While few components are needed, it is important to understand how performance can be affected by temperature, supply voltage, component tolerance and parasitic printed circuit board (PCB) effects. Figure 1 shows an example of a circuit that uses such an oscillator.

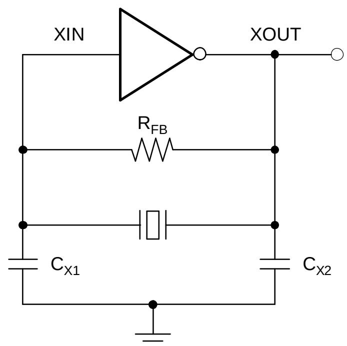


**Figure 1. Parallel Resonant Oscillator Circuit**

## 2 Quartz Crystal Equivalent Circuit

A quartz crystal is a piezoelectric device that, when placed in an electric field, causes a physical displacement or vibration to occur. This vibration translates to electrical properties that can be modeled using the circuit shown in Figure 2.

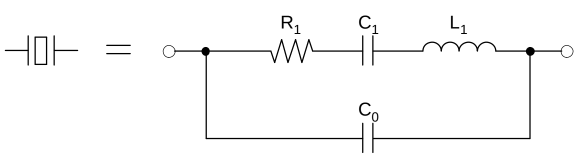


**Figure 2. Crystal Equivalent Circuit**

$C_1$, $R_1$ and $L_1$ are the motional arm of the crystal or resonator. Capacitor $C_0$ is the package and other parasitic capacitance that shunts the motional components. Figure 3 shows the impedance versus frequency of a 2MHz crystal.

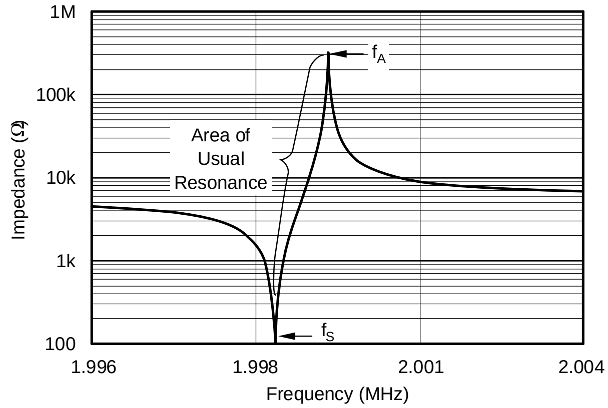


**Figure 3. 2MHz Crystal Equivalent Circuit Impedance versus Frequency**

### 2.1 Series and Parallel Resonance

Series resonance $f_S$ occurs when the conditions described by Equation 1 are satisfied.

$$f = f_S = \frac{1}{2\pi\sqrt{(L_1 \cdot C_1)}} \tag{1}$$

Series resonance happens when the inductive reactance of $L_1$ is equal to the capacitive reactance of $C_1$. Since these impedances are 180° out of phase, they cancel out each other, leaving $R_1$ as the impedance between the crystal terminals.

Parallel resonance occurs at frequency $f_A$. This happens when inductor $L_1$ reacts with the total capacitance seen between its terminals. This is also known as the anti-resonant frequency and is defined by Equation 2 and Equation 3.

$$f = f_A = \frac{1}{2\pi\sqrt{\left[L_1 \frac{\left(C_1 \cdot \left(C_{LOAD} + C_0\right)\right)}{\left(C_1 + C_{LOAD} + C_0\right)}\right]}} \tag{2}$$

$$C_{LOAD} = \frac{[C_{X1} \cdot C_{X2}]}{[C_{X1} + C_{X2}]} \tag{3}$$

## 2.2 Area of Usual Parallel Resonance

Figure 4 shows that at frequencies below $f_S$ and above $f_A$, the impedance is mostly capacitive. Signals that occur at frequencies in between $f_S$ and $f_A$ are seen as inductive.

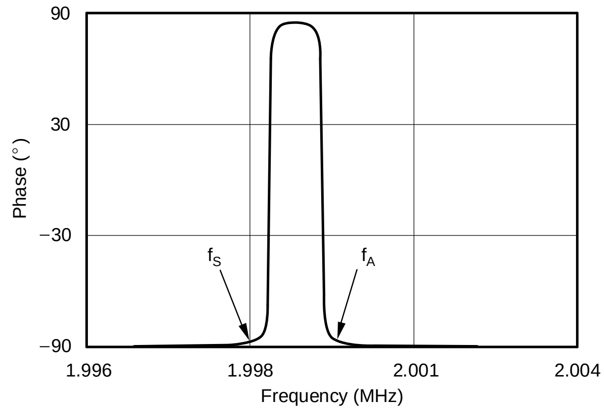


**Figure 4. 2MHz Crystal Equivalent Circuit Phase Response versus Frequency**

Oscillation will typically occur at a frequency $f_{OSC}$, where:

$$f_S \le f_{OSC} \le f_A \quad (4)$$

This frequency interval is referred to as the *area of usual parallel resonance*. The 180° phase shift in impedance here allows for the signal delay that is required for oscillation. Some typical component values are shown in Table 1.

**Table 1. Typical Motional Component Values**

| FREQUENCY (MHz) | $R_1$ (Ω) | $L_1$ (mH) | $C_1$ (pF) | $C_0$ (pF) |
|---|---|---|---|---|
| 2 | 100 | 520 | .012 | 4 |
| 4.608 | 36 | 117 | .01 | 2.9 |
| 11.25 | 19 | 8.38 | .024 | 5.4 |

## 3 Oscillation

When power is applied to an oscillator circuit such as the one shown in Fig. 1.0, the inverter amplifies noise and transient signals. The feedback network (shown in Figure 5) acts like a band-pass filter, allowing only signals between $f_A$ and $f_S$ to pass to the amplifier input with maximum gain. This network also provides the delay required for oscillation.

Figure 5 shows an open-loop Pierce oscillator circuit used in obtaining the gain and phase response shown in Figure 6.

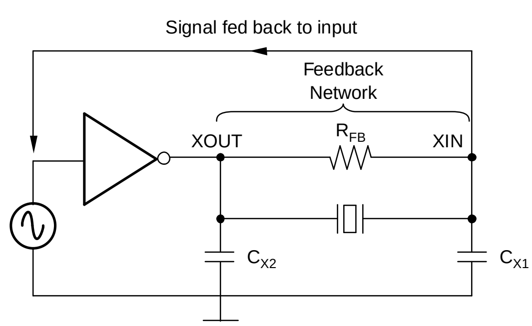


**Figure 5. Open-Loop Pierce Oscillator Circuit**

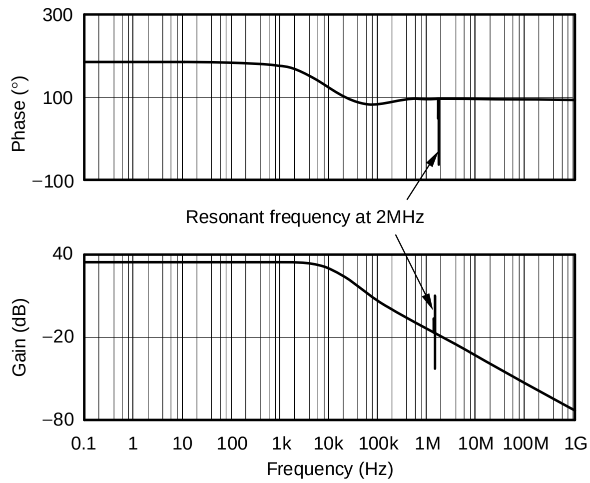


**Figure 6. Gain and Phase Response of Open-Loop Oscillator Circuit**

The resonator is tuned to a resonant frequency of 2MHz. Note the phase drop and bump in gain that occurs at 2MHz. Since the phase drops to below 0° and the gain is above unity, this small signal analysis indicates that the circuit will oscillate.

Oscillation begins when the total phase shift through the inverter and feedback circuit is *N*360*° and the gain around the loop is greater than unity (with *N* being an integer normally equal to 1). The inverter provides the gain at the frequency of interest in order to amplify the signal. The signal amplitude will increase until the non-linear response of the amplifier limits the gain around the loop to unity. If the amplifier has too much gain, this can lead to clipping. Piezoelectric devices can be damaged if the power dissipated across them exceeds the rated specifications for the given device. Techniques for avoiding this type of excessive dissipation will be discussed later in this report.

Components and parameters that affect oscillator startup and performance include the crystal resonator, inverter gain and phase, external capacitors $C_{X1}$ and $C_{X2}$, parasitic PCB capacitance, temperature and supply voltage. Each of these factors is discussed below.

## 4 Amplifier

The amplifier provides the needed gain for oscillation, and when used as an inverter (as in Figure 1) , it also provides 180° of phase delay. Too much gain at the desired frequency of oscillation can lead to excessive power dissipation and may even damage the crystal if it is not protected. Alternatively, insufficient gain can lead to start-up problems. Keep in mind that gain will vary with temperature and supply voltage. The amplifier design should be robust to insure that the oscillator will start up under all specified conditions.

Typically, high temperature and large supply voltage reduce the gain of a two transistor inverter. Care should be taken to insure that oscillation begins under all conditions.

Gain and phase analysis assumes a small signal response—that is, the signal level is low in amplitude. In reality, though, it is not unusual for an oscillator output to be a large signal and clipped at one supply rail (or both). Large signal effects such as slew rate can create a propagation delay which is not accounted for in the small signal gain/phase analysis. Oscillations typically begin as small signals and grow exponentially as shown in Figure 7 and Equation 5.

$$V(t) \approx e^{\alpha t} \cdot \sin(\omega t + \Phi) \quad (5)$$

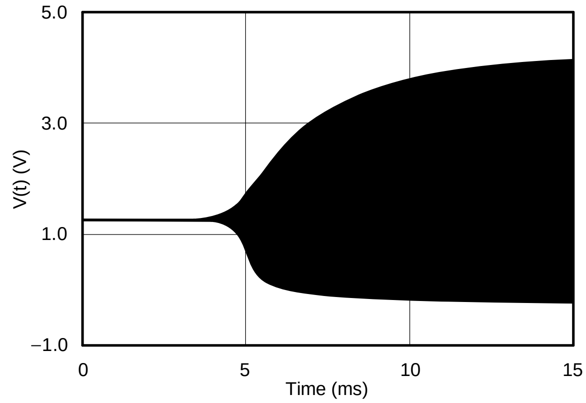


**Figure 7. Start-Up for 2MHz Crystal Oscillator Circuit**

As the oscillations grow in amplitude and the amplifier enters into its non-linear region of operation, gain is reduced. Once the overall loop gain is unity, the oscillating signal will reach its steady state amplitude and frequency.

## 5 Load Capacitors $C_{X1}$ and $C_{X2}$

These components account for 90° of the required 360° of phase shift. Operation in the region of usual parallel resonance is influenced by these components, whose total value also includes PCB and amplifier parasitic capacitance. Frequency pulling from the series resonant frequency $f_S$ is defined by Equation 6.

$$\Delta \frac{f}{f_S} = \frac{C_1}{2 \cdot (C_{LOAD} + C_0)} \quad (6)$$

The high Q of the crystal limits the amount of frequency pulling that can occur because of this, but variances from $f_S$ can be up to .01%. These capacitors can also greatly affect the oscillator startup time, or even whether the oscillator starts up at all.

Crystal manufacturers typically trim the quartz with the specified load capacitance in place. Thus, crystals with a rated load capacitance of 12.5pF have been trimmed so that the specified frequency of oscillation occurs with this load. Note that this is not the value of the $C_{X1}$, $C_{X2}$ capacitors coupled to ground; it is the series capacitance of both $C_X$ components. So, if $C_{X1}$ is equal to $C_{X2}$, they would each be 25pF in order to meet the 12.5pF specified load.

## 6 Feedback Resistor $R_{FB}$

This resistor aids in setting the DC bias point at the input of the amplifier. In some cases where the amplifier is a Schmitt trigger, relaxation mode oscillations can begin. Typically, this resistor is in the order of one MΩ. If the value is too low, the closed loop gain is reduced and the circuit may not begin to oscillate.

## 7 Quartz Resonators

A quartz crystal resonator is a piezoelectric device that can operate at up to hundreds of MHz. While mechanical in nature, the high Q at resonance translates into desirable electrical characteristics that can be used for setting clock frequencies with accuracy and stability over time, voltage and temperature.

Quartz is made of silicon and oxygen, and is the crystalline form of silicon dioxide. When synthesized, it is cultured under high pressure and temperature. A quartz crystal occurs as a six-sided prism with pyramids at both ends. In its raw form, it is called a *boule*. See Figure 8.

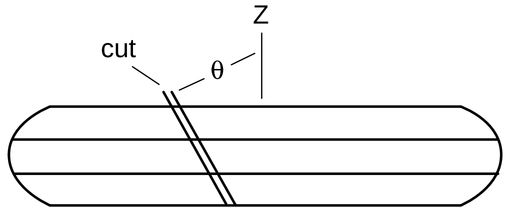


**Figure 8. Crystal Boule**

The boule is cut into thin plates called blanks. The angle and thickness of the cut determine the electrical characteristics of the device. Electrodes are then put on the blanks, either by electroplating or evaporative plating. The most common type of cut is an *A-T* cut. This type of cut is used to create crystals with resonant frequencies in the range of 1MHz and above. The stability over temperature is an *S*-shaped curve like the one shown in Figure 9.

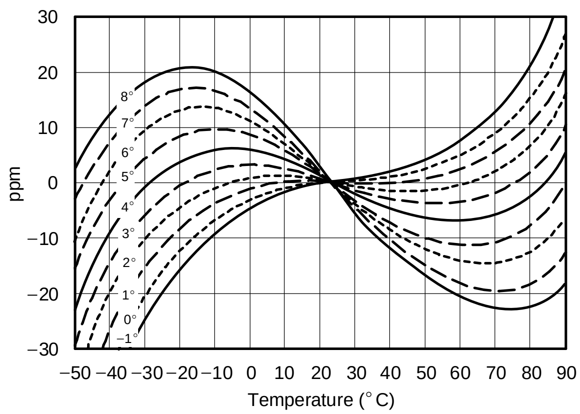


**Figure 9. A-T Cut Quartz Resonator Stability versus Temperature**

## 7.1 *32.768kHz Quartz Resonators*

An *N-T* type (or tuning fork cut) is used to create crystals that resonate at lower frequencies such as a 32.768 kHz time crystal. This geometry allows for a low resonant frequency with less crystal mass. As shown in Figure 10, the temperature stability has a parabolic shape and is in the order of –.04ppm/°C$^2$.

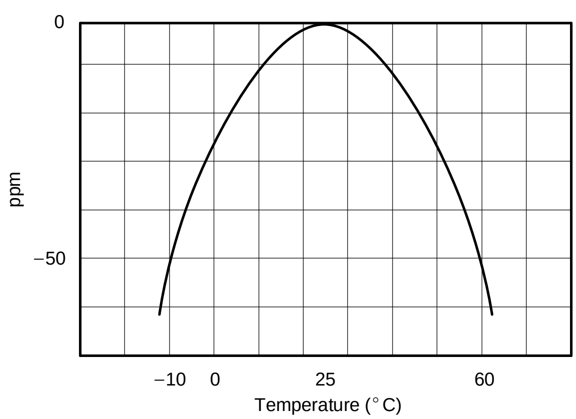


**Figure 10. Tuning Fork Cut Quartz Resonator Stability versus Temperature**

The frequency stability of a quartz crystal as a factor of aging is typically less than 3ppm over time. Frequency accuracy can usually be calibrated to within ± 20ppm of the specified nominal frequency. This is a function of external load capacitors $C_{X1}$, $C_{X2}$. The high Q of the crystal minimizes the amount of frequency pulling that can occur, which was shown in Equation 6. This allows for minimum variation of the nominal or desired clock frequency as a result of component tolerance.

## 7.2 Specified Load Capacitance

The specified load capacitance is important because the quartz is cut and tuned to the specified nominal frequency with this capacitance in the circuit. When the crystal is used in a Pierce oscillator configuration (see Figure 1), the values for $C_{X1}$ and $C_{X2}$ should be such that the series combination of both, plus the estimated parasitic PCB capacitance, equals the specified load capacitance.

## 7.3 Equivalent Series Resistance (ESR)

The equivalent series resistance (ESR) is the resistance of the crystal resonator when driven at the resonant frequency. This is not necessarily the $R_1$ value shown in Figure 2. The ESR of the oscillator circuit can be calculated using Figure 1, Figure 2 and Equation 3, where:

$$R_{ESR} = R_1 \cdot \left(1 + \frac{C_0}{C_{LOAD}}\right)^2 \quad (7)$$

This value is typically monitored when tuning the quartz crystal to the specified resonant frequency. $R_{ESR}$ is sometimes specified as a maximum resistance and should be used when determining the drive level of the oscillator (discussed in the next section).

## 7.4 Drive Level

The maximum drive level is an important specification because the crystal may be damaged by over-stressing it with excessive current. Most crystals with nominal frequencies greater than 600kHz are rated at 1mW or 2 mW. This is not usually a problem. Low-frequency N-T or tuning fork crystals, such as 32.768kHz watch resonators, are much less tolerant. These are rated for a maximum power dissipation of 1µW or lower. However, excessive vibration can damage the crystal so that the device will not function or shift upward in frequency because of mass loss. Figure 11 shows the power measurement of a 32.768kHz crystal.

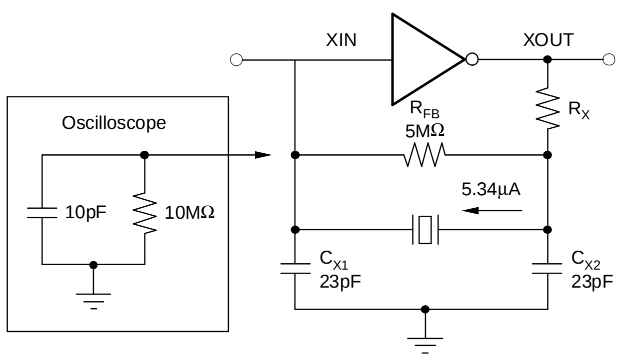


**Figure 11. Power Measurement of 32.768kHz Crystal**

The drive level can be estimated by using Equation 7 and Equation 8.

$$P = I^2 \cdot R_{ESR} \quad (8)$$

where for P = 1µW and $R_{ESR}$ = 35kΩ maximum, the $I_{RMS}$ current through the crystal should be limited to 5.34µA.

The best way to monitor for this is to clamp a current probe next to the crystal. If one is not available, an alternate solution is shown in Figure 11. At resonance, most of the current coming into node XIN is through the crystal. This current is coupled to ground through capacitor $C_{X1}$ and the oscilloscope input capacitance. By observing the signal here with an oscilloscope and using Equation 8 through Equation 10, one can estimate the power dissipated in the crystal.

Reactance of capacitance at node XIN is shown in Equation 9:

$$X_C = \frac{1}{2\pi[23pF + 10pF] \cdot 32,768kHz} = 147,257\Omega \quad (9)$$

The 10pF input scope capacitance is added to $C_{X1}$ in order to determine the input reactance $X_C$. Since the 10MΩ scope resistance is much greater, it can be ignored. The maximum sinusoidal voltage can be calculated using $X_C$ from Equation 9 and the calculated $I_{RMS}$ from Equation 8 as shown in Equation 10.

$$V_{MAX} = I_{RMS}(crystal) \cdot X_C \cdot 2 \cdot \sqrt{2}$$
$$V_{MAX} = 5.34\mu A \cdot 147,257 \cdot 2 \cdot \sqrt{2} = 2.2V_{PP} \quad (10)$$

Current coming through the 5MΩ resistor is ignored in this calculation, but may be significant in some applications. If this is the case, the calculated $V_{MAX}$ is a pessimistic value and can be considered guard-banded.

$R_X$ can be adjusted in order to achieve the desired $V_{MAX}$. Typical values are around 200kΩ.

## 7.5 *Overtones and Spurious Modes*

The vibrational characteristics of a quartz resonator are such that they can resonate at frequencies other than the specified nominal frequency. Odd-ordered mechanical overtones are always present along with spurious responses that are usually 1kHz or 2kHz above each main response. Note that these are not harmonics, but different vibration modes. This effect can be modeled as shown in Figure 12.

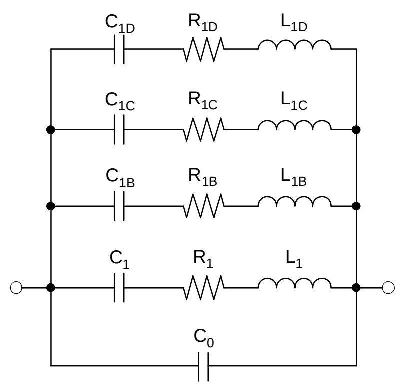


**Figure 12. Circuit for Overtone and Spurious Response**

High gain and bandwidth in the amplifier can allow the circuit to begin oscillating at one of these undesired frequencies. Reducing the amplifier bandwidth usually eliminates this effect. Increasing the value of the load capacitors can also eliminate this effect.

## 8 Clock Circuits for the MSC1210, MSC1211 and MSC1200

The MSC12xx family of data acquisition products includes an on-board inverting amplifier which can be interfaced with external components. This feature allows for various optimization options that can be tailored for specific needs and performance goals.

Capacitors should be NPO ceramic, polyester film or other comparable type. Quartz crystals are available from a variety of manufacturers. Make sure that temperature specifications, load capacitance, drive level and nominal frequency fit your specific application.

## *8.1 MSC1200 with 32.768kHz Crystal*

The MSC1200 supports the use of a 32.768kHz watch crystal, as shown in Figure 13. The drive level should be monitored to make sure that the power across the crystal does not exceed maximum specified levels. This is typically 1µW for most manufacturers. $R_{X1}$ is used to trim this limit. $R_{FB}$ should be 5MΩ.

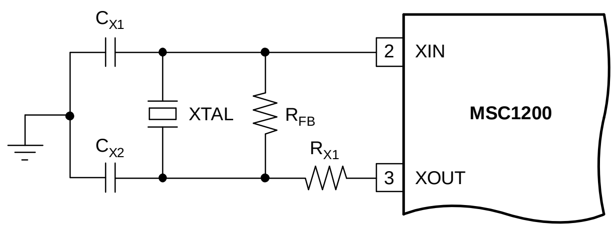


**Figure 13. MSC1200 32.768kHz Oscillator**

Note that Hardware Configuration Register 2 (HCR2) of the MSC1200 should be set to PLL High Frequency or PLL Low Frequency mode in order to use this circuit. See the MSC1200 product data sheet (available for download at www.ti.com) for more information.

**Table 2. Typical Component Values for MSC1200**

| | |
|---|---|
| $C_{X1}$, $C_{X2}$ | Use manufacturer-specified load capacitance. |
| $R_{FB}$ | 5MΩ. The MSC1200 does not include an internal $R_{FB}$ resistor. |
| $R_{X1}$ | Drive limiting resistor. A typical value would be 200kΩ. |

## *8.2 MSC1200, MSC1210, and MSC1211*

For frequencies ≥ 1MHz, the circuit shown in Figure 14 can be used. Note that for the MSC1200, Hardware Configuration Register 2 (HCR2) should be set for External Crystal mode. See the MSC1200 product data sheet for more information.

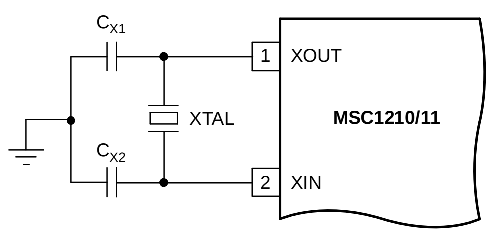


**Figure 14. Crystal Oscillator Circuit for MSC1200, MSC1210 and MSC1211**

**Table 3. Typical Component Values for MSC1200, MSC1210 and MSC1211**

| | |
|---|---|
| $C_{X1}$, $C_{X2}$ | Use manufacturer-specified load capacitance except as indicated in Table 5 and Table 6. |

## *8.3 Startup Issues*

For resonant frequency crystals > 4MHz, startup problems can arise because of parasitic and $C_X$ load capacitances limiting the bandwidth of the internal inverting amplifier. Removing or reducing the $C_{X1,2}$ load capacitors can resolve these problems.

Other potential startup problems can be avoided by using the negative resistance method[(1)] for testing the oscillator circuit. This technique is illustrated in Figure 15.

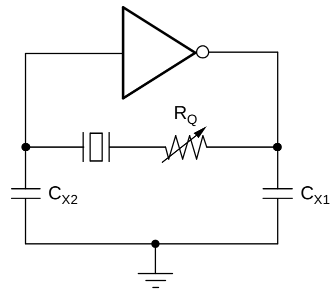


**Figure 15. Negative Resistance Measuring Circuit**

Resistor $R_Q$ is placed in series with the resonator. Startup is monitored while $R_Q$ is incrementally increased in value. The maximum value of $R_Q$ that can be obtained while still having the circuit startup is $R_{QMAX}$. This value is compared to the specified $R_{ESR}$ of the resonator. A safety factor is calculated using Equation 11.

$$\text{Safety factor} = \frac{R_{QMAX}}{R_{ESR}} \qquad (11)$$

The safety factor should be greater than a minimum value in order to insure reliable startup operation of the oscillator circuit over mass production and device lifetime. This qualification is summarized in Table 4.

**Table 4. Safety Factor vs Qualification**

| SAFETY FACTOR | QUALIFICATION |
|---|---|
| SF < 1.5 | Unsuitable |
| 1.5 ≤ SF ≤ 2 | Risky |
| 2.0 ≤ SF ≤ 3 | Might be suitable |
| 3.0 ≤ SF ≤ 5 | Safe |
| SF > 5 | Very safe |

Table 5 and Table 6 show data taken by Fox Electronics indicating the safety factor of some of their quartz resonator products and the MSC1210. Their measurements include the $R_{ESR}$ and negative resistance $R_{QMAX}$ measurement with a specific load capacitance and supply voltage. Notice how the reduction of load capacitor can increase the safety factor. The manufacturer's specified load capacitance is 20pF for all of these resonators.

**Table 5. 3.3V Supply**

| CRYSTAL | $C_{X1}$ (pF) | $C_{X2}$ (pF) | $R_{ESR}$ (Ω) | BOARD FREQUENCY (MHz) | $R_{QMAX}$ | SAFETY FACTOR |
|---|---|---|---|---|---|---|
| HC49S-11.0592 | 18<br>10 | 18<br>10 | 17.2<br>17.2 | 11.060372<br>11.061994 | 106<br>180 | 6.2<br>10.5 |
| HC49S-4.000 | 10 | 10 | 67 | 4.000533 | 1000 | 14.9 |
| HC49S-8.000 | 10 | 10 | 19 | 8.001152 | 600 | 31.6 |
| HC49S-12.000 | 10 | 10 | 15.2 | 12.002240 | 163 | 10.7 |
| HC49S-11.0592 | 10 | 10 | 14.8 | 11.061541 | 167 | 11.3 |
| HC49U-1.8432 | 10 | 10 | 188.1 | 1.843308 | 1000 | 5.3 |

**Table 6. 5V Supply**

| CRYSTAL | $C_{X1}$ (pF) | $C_{X2}$ (pF) | ESR (Ω) | BOARD FREQUENCY (MHz) | $R_{QMAX}$ | SAFETY FACTOR |
|---|---|---|---|---|---|---|
| HC49S-32.768 | 10<br>none | 10<br>none | 10.5<br>10.5 | 32.776717<br>32.789178 | 27<br>308 | 2.6<br>29.3 |
| HC49S-16.000 | 10 | 10 | 8.5 | 16.004292 | 200 | 23.5 |
| HC49S-25.000 | 10 | 10 | 11 | 25.006347 | 66 | 6 |
| HC49S-11.0592 | 10 | 10 | 14.8 | 11.061873 | 397 | 26.8 |
| HC49U-1.8432 | 10 | 10 | 188.1 | 1.843308 | 1000 | 5.3 |

### *8.4 Overtone Frequencies*

When using a 32.768kHz crystal, the oscillator can sometimes start up at some higher overtone frequency. Increasing the value of $C_{X1}$ or increasing $R_{FB}$ can band-limit the circuit so that oscillation starts at the fundamental 32.768kHz frequency.

## 9 References

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