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Crystal Oscillator Troubleshooting Guide

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1 Overview

This document is a quick-reference troubleshooting guide for solving crystal oscillator problems that might be encountered when working with microcontrollers.

A practical explanation of the Pierce and Colpitts oscillators used in Freescale microcontrollers and recommendations to help solve common problems with microcontroller crystal oscillators are presented in the following sections. Nevertheless, a particular problem might require a different solution from those proposed in this application note. Most of the points discussed will help in the design stage to come about with a more reliable oscillator.

2 Introduction

Most microcontrollers can use a crystal oscillator as their clock source. Other options include external canned oscillators, resonators, RC oscillators, and internal clocks. The main advantages of a crystal oscillator are frequency accuracy, stability, and low power consumption. However, high reliability is needed to fully benefit from these advantages.

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To solve common problems with crystal oscillators and to achieve high reliability, it is important to pay attention to the configuration used, the components and their values, and the layout. This paper will show how these elements affect such factors as crystal power dissipation, stability, variations with temperature, feedback strength, start-up time, noise immunity, and thus, reliability and correct operation. It also contains suggestions for solving problems in these areas.

3 Oscillator Configurations

The two most common oscillator configurations for microcontrollers are the Pierce and the Colpitts configurations. The M68HC08 and HCS08 microcontrollers implement the Pierce oscillator configuration.

The MC68HC12 and HCS12 microcontrollers use either a variation of the Colpitts configuration (the translated ground Colpitts configuration) or the Pierce configuration. In some microcontrollers both options are available and it is possible to choose between the two.

To select the best option when a choice is possible, it’s important to understand the respective advantages of the Pierce and the Colpitts configurations. The two configurations have a similar AC equivalent circuit, but the location of the common ground node differs. Many of the performance differences between these configurations can be attributed to the varying effects of stray reactances as the ground is moved and to the effects of the biasing elements.

In the Colpitts configuration stray reactances tend to appear across the crystal. This degrades performance and reliability, and the effect is worsened by biasing elements in this configuration. In the Pierce configuration, performance and reliability are considerably less affected because stray elements tend to appear across the load capacitors (i.e., stray capacitance tends to add to the load capacitors, so it’s easy to compensate by simply reducing the load capacitors' value).

Freescale’s Colpitts configuration provides an amplitude limitation control (ALC) loop which permits lower current consumption and lower levels of RF emissions. However, the Pierce configuration is less susceptible to noise, doesn't have a DC voltage across the crystal, and starts up faster.

Unless the lower current consumption of the Colpitts configuration is required, it is highly recommended to opt for the Pierce configuration due to its better reliability.

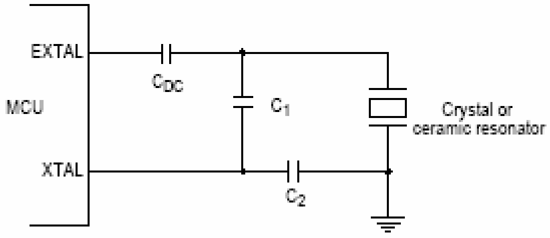

Figure 1. Colpitts Oscillator

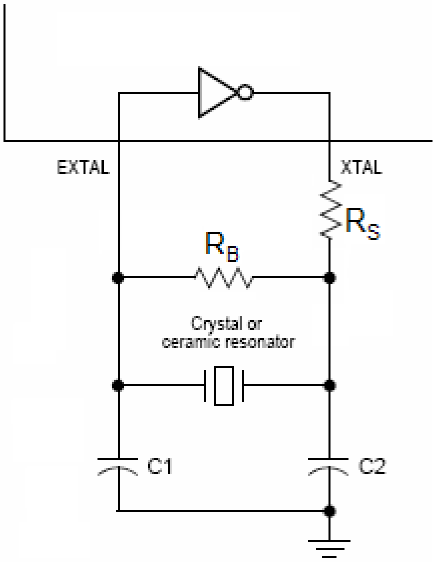

Figure 2. Pierce Oscillator

4 Components in the Colpitts Configuration

An important remark with the Colpitts configuration is that it produces a DC voltage across the crystal. This causes some crystals to age faster, and the specific effect will depend on the crystal's manufacturing process. Since this is a long-term reliability issue, problems won't be observed in the initial testing. To solve the problem, a capacitor can be added to block the DC voltage, as shown in Figure 1.

Consult the crystal manufacturer on the value for the capacitor and whether it should be included. If it’s impossible to consult with the crystal manufacturer, it is recommended that you add a capacitor to block the DC voltage. A good rule of thumb is to use a capacitor approximately 100 times the load capacitance of the crystal. The exact value is not critical, and should be a value around 1 nF.

The series combination of C1 and C2: (C1*C2) / (C1+C2), should give a value close to the load capacitance, C_L, specified by the crystal manufacturer. Be sure to consider stray capacitances when performing this calculation. Since the feedback voltage is taken from the voltage divisor made up from C1 and the crystal, increasing C1 will result in stronger feedback, while reducing its value will result in weaker feedback. Insufficient feedback could prevent oscillation from starting or make oscillation difficult to sustain. In the past, excessive feedback sometimes resulted in crystal overdrive. Crystal overdrive is very unlikely with modern ICs because they now operate at very low voltages.

5 Components in the Pierce Configuration

In general, the smaller the value of R_S (Figure 2), the faster the oscillator will start. R_S must be large enough to avoid overdriving the crystal, yet small enough to provide enough current to start oscillation quickly (an R_S that’s too large could cause the oscillator to fail to start). R_S can in some cases be zero (shorted), especially with high-frequency crystals.

R_B, also known as feedback resistance (Rf) and shown in Figure 2, is used to bias the input of the inverting amplifier. By pulling the input of the amplifier toward the voltage at the output, an unstable condition is created, stimulating oscillation. It can also be observed that feedback resistance affects the loop gain of the amplifier, which is augmented as the value for the feedback resistance is increased.

The value for capacitors C_1 and C_2 must be chosen so that the series combination: $(C_1 * C_2) / (C_1 + C_2)$ gives a value close to the load capacitance, C_L, specified by the crystal manufacturer. Be sure to add stray capacitances in the previous calculation. Occasionally, C_1 can be chosen to be slightly smaller than C_2 to increase the voltage swing at EXTAL without compromising stability; using a trimmer capacitor in lieu of C_1 or C_2 can help find the ideal value.For most applications it is recommended to have the same value for C_1 and C_2.

6 Crystal Overdriving

Overdriving a crystal can create a number of problems, from high RF emissions and added power consumption to long-term reliability issues (physical damage to the crystal) to the crystal attempting to start at an overtone, or failing to start at all. This is more common with low-frequency crystals, since the maximum power they can dissipate (maximum drive level) is typically much lower than what is specified for high-frequency crystals.

The total power the crystal will have to dissipate depends on several factors. It is proportional to R_1, the series resistance of the crystal. It is also proportional to the square of: the voltage across the crystal, frequency, and total capacitance, $C_0 + C_L$.

Assuming the peak voltage across the crystal is close to V_{DD}, the following formula provides a rough approximation for the power dissipated by the crystal:

$$P = 2 \times R_1 \left[\pi \times freq. \times V_{DD} \times (C_L + C_0)\right]^2 \quad \textbf{Eqn. 1}$$

This formula makes use of the fact that at resonance, the impedance of the motional arm of the crystal is equal to the impedance of $C_L + C_0$ (load capacitance + shunt capacitance of the crystal). In oscillators with amplitude limitation control (ALC), V_{DD} should be replaced with the maximum voltage amplitude obtained (approximately 400 - 600 mV).

To reduce the power that has to be dissipated by the crystal the following could be done:

- Specify a lower maximum series resistance, $R_{1(max)}$, to the crystal manufacturer
- Reduce C_L (reducing capacitors C1 & C2)
  This must be done carefully, since it could increase the voltage across the crystal, which would, in turn, increase the power.
  Reducing load capacitance will slightly increase the frequency of oscillation.
- For the Pierce configuration, add or increase the value of the series-damping resistor, R_S. Crystal overdriving is not a common problem with the Colpitts configuration.

It is important to have a good margin of safety between the power dissipated and the maximum drive level specified by the crystal manufacturer in part because loop gain can increase with colder temperatures and higher supply voltages, increasing the risk of overdriving the crystal.

7 Insufficient Loop Gain

Just as overdriving the crystal can be a problem, insufficient drive can also be the source of many failures. For adequate loop gain, load capacitors must be sized correctly, and R_B and R_S values must be appropriate in the Pierce configuration.

Load capacitance affects loop gain since the feedback voltage is obtained in both configurations from the voltage divider formed by C_1 and the crystal, so it is very important to account for stray capacitance when calculating the value of C_1 and C_2. In the Pierce configuration, adding load capacitance will reduce loop gain in some cases.

Resistors R_B and R_S also have an effect on loop gain in the Pierce configuration. Making R_B bigger increases the loop gain, while reducing R_B decreases it. In general, lower-frequency crystals require higher values for R_B because their impedance is normally higher than that of high-frequency crystals. A typical value for R_B is usually given in the microcontrollers' datasheet. Resistor R_S has the opposite effect on loop gain, since loop gain is reduced when the resistor is increased and is increased when the resistor is reduced.

To make sure that loop gain is sufficient, a potentiometer can be placed in series with the crystal. If loop gain is barely sufficient, increasing the resistance will soon prevent the oscillator from starting. The recommended procedure is to start with the potentiometer set at 0 Ω, then slowly increase the resistance. After each increment, power to the board should be removed and then restored. Eventually, the circuit will fail to start. When this happens, the total resistance (crystal + potentiometer) should be substantially larger than the worst-case resistance specified for the crystal. For example, for a good margin of safety, it would be nice to have the circuit oscillate with at least twice the maximum specified crystal resistance. The size of the potentiometer required for the test will increase as the crystal frequency decreases (i.e., 1 kΩ for a 10 MHz crystal and 10 kΩ for a 32 kHz crystal).

It is recommended that the previous test also be carried out at the highest temperature and lowest V_{DD} at which the circuit is expected to operate, since loop gain in many oscillators tends to decrease as temperature increases and as V_{DD} decreases.

8 Long Start-Up Time

A long start-up time is usually a more common problem with low-frequency crystals, since they tend to start much more slowly than high-frequency crystals. One of the causes of a long start-up time is weak loop gain, which was addressed in Section 7, “Insufficient Loop Gain”. Oscillator start-up times will also be affected by the rise time of the power supply. When the power supply has a sharp rise time, the crystal will experience an energy impulse that will usually make it start faster than it would using a power supply with a slow rise time.

9 Temperature and Voltage Issues

The circuit should be tested over the entire temperature and voltage range in which it is expected to operate. Tests are especially important at the highest temperature and lowest supply voltage, which lead to minimum loop gain and could result in a slow or no start-up. It’s also important to test at the coldest temperature and highest supply voltage, which lead to maximum loop gain and could overdrive and damage the crystal, force it to oscillate at an overtone or harmonic, or cause it to stop working.

If possible, testing under both low- and high-humidity conditions is also recommended. To minimize undesirable temperature effects, use capacitors with a low temperature coefficient, such as NP0 or COG types. Verify that all components are specified to work for the entire temperature and voltage range, especially the crystal.

10 Noise Immunity

Noise is a common cause of oscillator failures; therefore, it’s important to know how to make the oscillator as immune to noise as possible and to know how to identify when noise is the source of the problem. One of the easiest ways to know when noise is the problem is if the oscillator malfunction appears when a big load is activated (i.e., a motor), or a power or high-frequency trace is activated. A noise problem is also indicated if the problem appears when another device is turned on or when it is brought nearby, because noise could be conducted or radiated.

To make the oscillator circuit more resistant to noise, make sure there’s an adequate loop gain with good margin; see Section 7, “Insufficient Loop Gain” . It is also important to check for a good amplitude level. Some microcontrollers can be configured to provide a higher amplitude output for improved noise immunity, although higher current consumption is a drawback. Other microcontrollers, especially those that implement Colpitts oscillators, have non-adjustable on-chip amplitude limitation control (ALC) loops that make increasing the amplitude level impossible.

Proper layout is also critical in attaining good noise immunity. Traces must be as short as possible. Besides adding stray elements, long traces absorb and radiate more noise since they act like antennas. Route power and high-frequency traces far from the oscillator circuit to minimize noise coupling. In some cases, it might be convenient to shield the oscillator circuit to further isolate it from noise sources. One way to accomplish this is by surrounding the circuit with a wide grounded trace. For this to work, the grounded trace must have zero current flowing through it. This is why data sheet examples use a “floating ground” with no connections other than the oscillator’s V_{SS}. Finally, ensure adequate power supply decoupling and filtering to minimize noise in the power supply.

11 Layout Issues

Good layout practices are fundamental to the correct operation and reliability of the oscillator. It is critical to locate the oscillator’s components very close to the XTAL and EXTAL pins to minimize routing distances. Long traces in the oscillator circuit are a very common source of problems. Don't route other signals across the oscillator circuit, and make sure power and high-frequency traces are routed as far away as possible to avoid crosstalk and noise coupling. Power supply decoupling capacitors should be located very close to the microcontroller’s power pins.

Avoid the use of vias; if the routing becomes very complex, it is much better to use 0 Ω resistors as bridges to go over other signals. Vias in the oscillator circuit should only be used for connections to the ground plane. Don't share ground connections; instead, make a separate connection to ground for each component that requires grounding. If possible, place multiple vias in parallel for each connection to the ground plane.

Especially in the Colpitts configuration, the oscillator is very sensitive to capacitance in parallel with the crystal or resonator. Therefore, the layout must be designed to minimize stray capacitance across the crystal or resonator. For example, in the Colpitts configuration, it’s possible to remove the ground plane from all layers under the EXTAL trace and to leave considerable spacing from the EXTAL trace to all other traces and planes. When stray capacitance appears across capacitors C_1 and C_2, they should be resized to compensate for this added capacitance. Be sure to take into account both printed circuit board (PCB) and pin capacitance.

The use of high-quality components in the oscillator circuit is equally important to achieve correct and reliable operation. The use of low-inductance resistors, such as carbon composition resistors, is recommended. Capacitors should be high-quality capacitors with very low ESR, designed for use in high-frequency applications (i.e., NP0 and COG). If a resonator is used, it is critical to choose a very high-quality resonator.

Remember that poor layout practices (like long traces) can also contribute to EMC susceptibility and unintentional electromagnetic radiation.

12 Other Problems

Other common problems include the build up of contaminants on the PCB, hermetic seal fracture, and issues caused by an inadequate soldering process.

PCB contaminants, like flux, humidity, and finger prints, can reduce the impedance between nodes, which in turn can create a number of issues. To overcome this problem, check for contaminant accumulation between the crystal leads and beneath sufrace mount technology (SMT) devices.

Although uncommon, it is possible for a crystal’s hermetic seal to fracture. This would allow moisture and other contaminants to infiltrate the case, causing sporadic operation or complete failure. To avoid this problem, the crystal should be handled carefully and its case should be adhered to the PCB. A small SMT-type crystal is recommended.

Excessive temperatures or excessive exposure time to high temperatures due to an inappropriate soldering process can also damage the crystal. Make sure the soldering process is compatible with the crystal’s soldering profile.

13 Conclusion

After following best design practices, if the oscillator doesn't work properly, it is possible that the selected crystal (or resonator) has poor operating characteristics. In that case, consider choosing a different crystal, but remember that the new crystal’s required external component values will probably be completely different. Selecting an appropriate high-quality crystal is a very important part of the design process and is critical to achieving correct operation and high reliability.

Once the oscillator design has been optimized, it’s possible to further increase reliability through software. Many microcontrollers now have the capability to monitor clock quality and include tools like loss of clock interrupts to respond to oscillator problems.

Consult the microcontroller's datasheet for specific recommendations and the electrical specifications section for electrical and timing characteristics. If possible, consult the crystal or resonator manufacturer with respect to the component values. Many crystal manufacturers will validate your application board with their crystal or resonator and such an evaluation is strongly recommended.

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