November 2018

QUARTZ CRYSTAL TECHNOLOGY OVERVIEW

A clock signal provides the heartbeat of an electronic system, controlling the timing of events and synchronizing communication – both within and between systems.

This white paper will introduce some of the types of clock circuits available, and explain how they differ, the requirements for particular applications and the things you need to consider when you design-in a clock source. There is a particular focus on crystal oscillators as the most important class of clock circuit.

ROLE OF THE CLOCK

Most electronic systems today are based around a microcontroller, an application-specific integrated circuit (ASIC) or a system-on-chip (SoC). These contain one or more embedded processors with on-chip memory, peripherals and external interfaces. The speed at which a processor executes instructions, the movement of data to and from memory, the operation of peripherals, and the data rates of external interfaces are all driven by appropriate clock signals.

Microcontrollers typically have a clock input with a frequency of around 15 MHz. This is used to generate all the different frequencies required inside the device for the bus, processor cores, IO pins and other interfaces. Other components in the system may have their own oscillators.

A real-time clock (RTC) typically has an input frequency of 32.768 kHz, because this can be easily divided by powers of two to generate timekeeping signals down to one cycle per second.

These also need to be very low power, as the RTC in a system continues to run even in standby mode. Ethernet controllers require a highly accurate clock, usually with a frequency of 10 or 25 MHz.

Accurate oscillators are also important in radio frequency (RF) applications, where they provide a stable reference for GPS, radar and communications systems. It is essential that the transmitter and receiver use the same frequency within narrow bounds so they can filter out unwanted signals and track changes in frequency.

The clock technology chosen also needs to balance system requirements, such as cost and power consumption, against technical demands, such as frequency and stability.

TYPES OF CLOCK CIRCUIT

One of the simplest types of oscillator uses a resistor-capacitor (RC) resonant circuit. More accurate oscillators can be constructed using ceramic or crystal resonators.

In either case the oscillator circuit can be internal or external. External oscillators can be constructed from discrete components or use an integrated oscillator.

RC OSCILLATORS

An RC oscillator uses a tuned circuit to define the frequency of oscillation. It consists of an amplifying device such as an op-amp or a transistor, with the output fed back to the input via a network of resistors and capacitors to achieve positive feedback at a specific frequency.

This is a simple and cheap solution, but the disadvantages are that it can lack accuracy and stability.

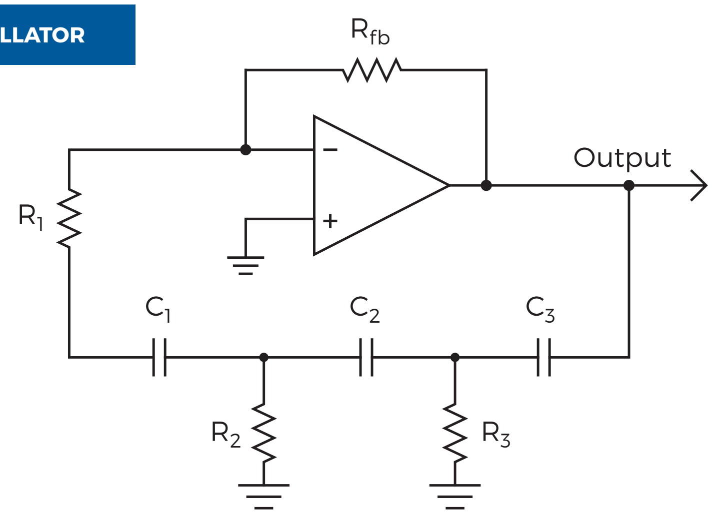
Some ICs provide the option to use an internal RC oscillator; this may be the default if no external clock is provided. The accuracy of this depends on the tolerance and stability of the components that make up the oscillator circuit. The output frequency can vary with changes in supply voltage or temperature. The accuracy and tolerance of the oscillator should be specified on the device datasheet.

Changes in frequency can affect external interfaces. For example, serial interfaces such as RS232 or USB need to work within a specific frequency range in order to synchronize and successfully communicate with other devices. Changes in frequency could also affect the timing of events, which may be important for real-time systems.

Some devices provide the option to adjust the frequency with an external trimming resistor, but this may need to be different for each device and so is only practical for low-volume products.

An RC circuit can also be used to make a variable frequency oscillator, which is useful if a wide frequency range is more important in your application than high accuracy.

FIGURE 1. RC OSCILLATOR



November 2018

CRYSTAL RESONATOR

To provide a more stable and accurate frequency reference, a crystal resonator can be used instead of an RC circuit. This uses the natural resonant frequency of a quartz crystal to control the frequency of oscillation. This is very stable due to its extremely high quality (Q) factor. Crystals are also small and inexpensive for many common applications.

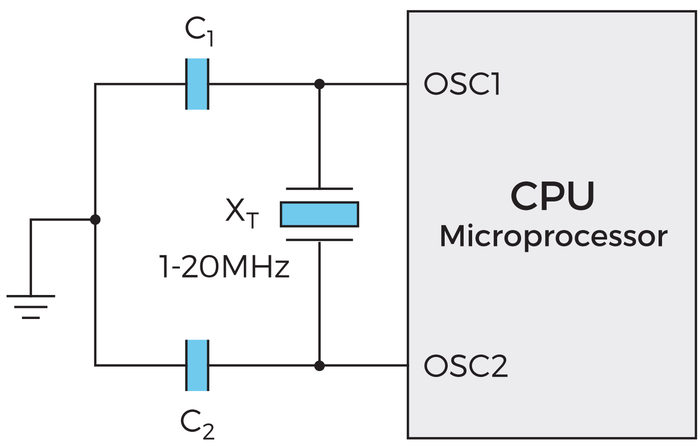
The crystal is a passive device and needs to be part of an oscillator circuit. This uses an inverting amplifier to provide gain and feedback in order to drive the crystal at its operating frequency.

The oscillator circuit may be integrated into the device that requires the clock, in which case you just need to connect the crystal and two ceramic load capacitors across the appropriate pins. These capacitors are typically around 10 to 33 pF.

It is important to keep the PCB traces from the pins to the crystal and capacitors as short as possible to minimize parasitic capacitance and inductance. The routing should also be symmetrical to ensure that the stray capacitance on both pins are equal.

Alternatively, you can use an external oscillator circuit. This can be constructed with discrete components or it can use an integrated oscillator module.

FIGURE 2. USING AN INTEGRATED OSCILLATOR



Diodes Incorporated offers a comprehensive portfolio of quartz crystals:
www.diodes.com/products/connectivity-and-timing/crystal-and-crystal-oscillator/xtals-crystals/

November 2018

CRYSTAL OSCILLATOR OPERATING THEORY

A quartz crystal resonator uses the piezoelectric effect. This means that if pressure is applied, a voltage will be generated across the faces. Conversely, applying a voltage will cause deformation of the crystal.

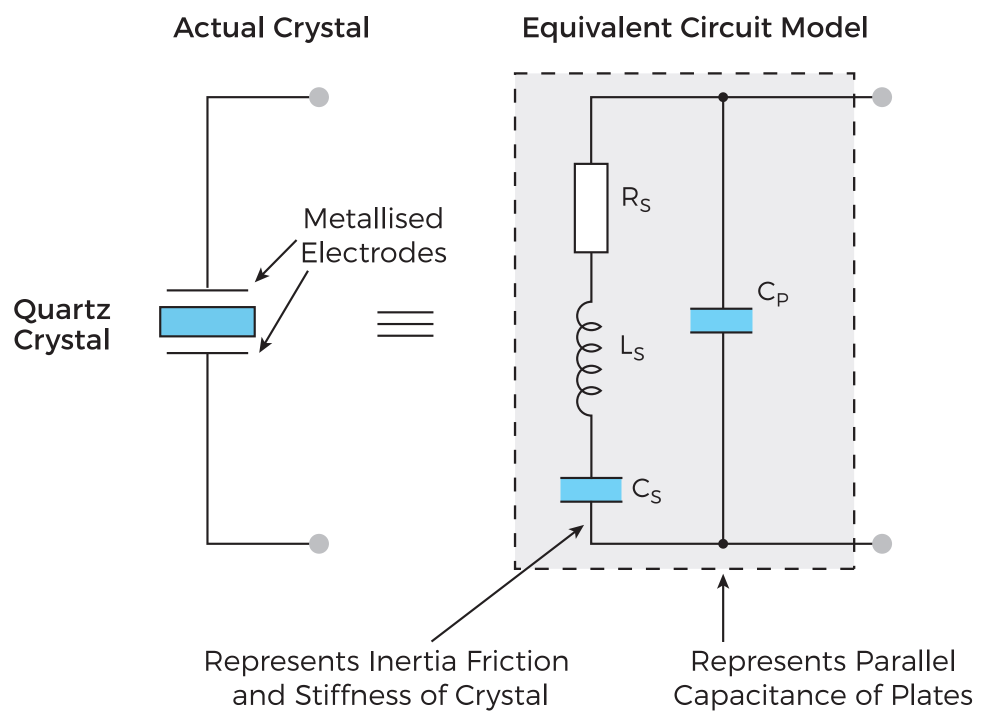
An electronic circuit can measure the voltage across the crystal and use feedback to cause the crystal to oscillate at its natural resonant frequency. Electrically, this appears equivalent to a resistor-inductor-capacitor (RLC) network.

The crystal resonator itself consists of a thin piece of quartz cut to have two parallel surfaces. These are given a metallic coating in order to make the electrical connections.

The size and thickness of the crystal defines the fundamental, or characteristic, frequency of oscillation.

In many cases, multiple frequencies are required in a circuit (for example, a microcontroller might have a high-speed processor while the bus and memory system runs at a lower speed). The output of an oscillator can be divided to produce lower-frequency clock signals. A phase-locked loop can be used to produce clocks that are a multiple of the input frequency.

FIGURE 3. CRYSTAL EQUIVALENT CIRCUIT



November 2018

OSCILLATOR CIRCUITS

A crystal oscillator requires a high-gain inverting amplifier. This can use a transistor or an inverting logic gate.

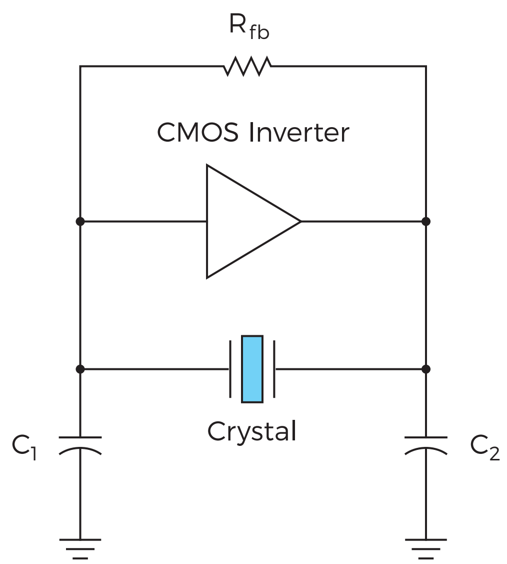
The values of resistors and capacitors in the circuit depend on various factors, such as the gain of the inverter, frequency stability, power consumption, crystal characteristics, startup time, etc. Most crystal vendors will provide design guides to help with calculating the required values. We will mention some of the factors that need to be considered, for example see **Load capacitance**, below.

The two most common types of oscillator circuit used in microcontrollers are the Pierce and Colpitts oscillators. These each have advantages and disadvantages, so some devices give the option to choose the type that best matches your requirements.

In the Colpitts oscillator, stray capacitance and inductance appear across the crystal. This degrades performance and reliability, and the effect is worsened by the biasing elements. A DC bias can cause some crystals to age faster. However, this configuration has a much lower power consumption.

In the Pierce oscillator, performance and reliability are considerably improved, because stray reactance appears across the load capacitors. This makes it easy to take the parasitic capacitances into account by adjusting the value of the external load capacitors.

FIGURE 4. PIERCE OSCILLATOR USING CMOS INVERTER



The Pierce configuration is also less susceptible to noise, starts up faster and doesn't put a voltage across the crystal.

When there is a choice, it is generally recommended to use the more reliable Pierce oscillator circuit, unless the lower power consumption of the Colpitts configuration is essential.

LOAD CAPACITANCE

To make a crystal oscillate at the specified frequency you must provide the correct equivalent load capacitance CL' (made up of C1 and C2, plus any stray capacitance). This must equal the CL value specified in the crystal datasheet. If CL' is too low the frequency will be higher than specified, while a larger capacitance results in a lower oscillation frequency. If the load capacitance is too far out either way then the oscillation may be unstable.

Crystals are available with a range of capacitive loads. You need to choose a crystal with CL that is within the range specified for the oscillator circuit.

The CL' seen by the oscillator includes all stray capacitances: the input capacitance of the crystal oscillator pins; the parasitic capacitance between the pads of the crystal; the PCB traces and the pads of the device to ground. The total value for these may be around 4 to 6 pF. (continued p6...)

November 2018

LOAD CAPACITANCE (CONTINUED)

The parasitic capacitance may be larger in RF designs if there is a ground plane on the PCB close to the traces and pads.

The actual value will vary, depending on the board layout and details of the components, and is difficult to calculate exactly. You can use an estimate and then check the result by comparing the oscillator frequency against that specified. If necessary, the values of the load capacitances, C1 and C2, can be adjusted to allow for the parasitic capacitance.

CRYSTAL OSCILLATORS (CXO)

You can also buy ready-made oscillator modules that contain a crystal and the oscillator circuitry. You just need to provide a power supply. This is often the simplest and most cost-effective solution where the device does not have an integrated oscillator circuit.

Oscillator modules are more accurate and stable than built-in oscillators. So, for applications that require very accurate clocks, such as Ethernet transceivers or RF systems, an external crystal oscillator module may be the best choice.

Diodes Incorporated has a range of high-quality oscillator modules that combine a quartz crystal resonator with the oscillator circuit:

www.diodes.com/products/connectivity-and-timing/crystal-and-crystal-oscillator/crystal-oscillator-cxo/

VOLTAGE-CONTROLLED CRYSTAL OSCILLATOR (VCXO)

A voltage-controlled crystal oscillator allows the frequency to be adjusted, or "pulled," within a small range by a control voltage. These are useful in RF and audio-frequency circuits, for example, as they allow the system to adjust the frequency to match an incoming signal, compensating for any small differences between the clocks.

The VCXO uses two variable-capacitance (varactor) diodes in the circuit to adjust the frequency. The varactor exploits the voltage-dependent capacitance of a reverse-biased p–n junction to create a voltage-controlled capacitor.

The key parameters of a VCXO include the center frequency, control voltage range, tuning frequency range ("pullability") and the clock jitter.

The pullability of a crystal is a measure of the frequency change for a given change of load capacitance or, equivalently, control voltage. A larger pullability implies a larger tuning range, but smaller values mean better stability and lower phase noise.

The range of frequency adjustment is typically a maximum of ±200 ppm, and the control voltage is normally from 0 to 2 or 3 V.

Diodes Incorporated also supplies a range of VCXO modules:

www.diodes.com/products/connectivity-and-timing/crystal-and-crystal-oscillator/vcxotcxovctcxo/vcxo/

November 2018

TEMPERATURE-COMPENSATED CRYSTAL OSCILLATOR (TCXO)

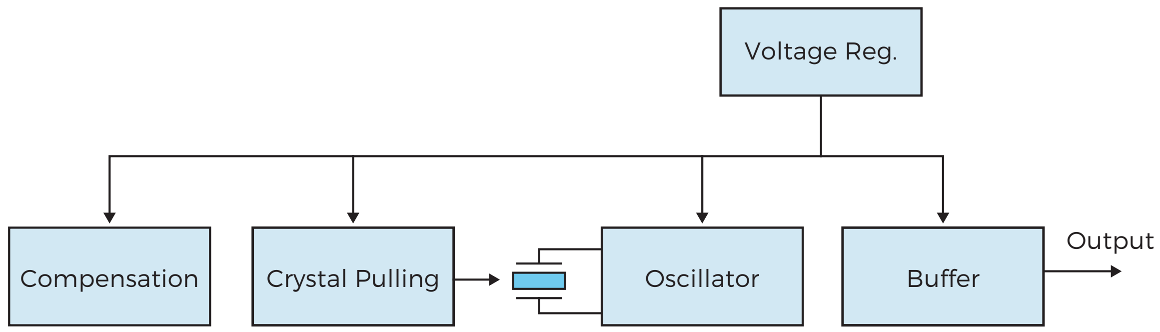
Although crystal resonators provide an accurate and stable reference frequency, they are still sensitive to temperature. Some applications need a much more stable reference. For example, GPS requires a stability of 0.5 ppm or less.

A temperature-compensated crystal oscillator (TCXO) can achieve stability better than 2 ppm by adjusting the frequency of a VCXO to compensate for changes in temperature as shown in the diagram below.

The behavior of the crystal can be described with a temperature-frequency response curve. The compensation circuitry needs to generate a control voltage that is the inverse of this curve. In the past this was done using analog components, but it can now be done more accurately and flexibly using digital control.

The TCXO will usually also include a voltage regulator to isolate the oscillator from changes in supply voltage.

FIGURE 5. TEMPERATURE-COMPENSATED CRYSTAL OSCILLATOR



The Diodes Incorporated range of TCXO modules compensate for variables such as ambient temperature, voltage and output loading:

www.diodes.com/products/connectivity-and-timing/crystal-and-crystal-oscillator/vcxotcxovctcxo/tcxo-vctcxo/

SPECIFYING & CHOOSING A CRYSTAL

Some of the characteristics to consider when choosing a crystal are summarized below. These should be defined in the datasheet for the crystal or oscillator module.

- **PACKAGE**: Crystals are available as surface mount devices (SMDs) and through-hole mounted.

- **FREQUENCY**: The specified characteristic frequency of the crystal, specified in kHz or MHz.

- **TOLERANCE**: The allowed deviation from the nominal frequency, normally specified in ppm. More accurate crystals are more expensive.

- **JITTER**: The short-term stability of the oscillator frequency. Excessive jitter can interfere with communications protocols and cause an increased bit error rate.

- **STABILITY**: How the frequency of the crystal changes with temperature and aging. The cut known as AT minimizes the variation around normal ambient temperature.

- **ESR**: Equivalent Series Resistance. The equivalent impedance of the crystal at its operating frequency. ESR values are generally stated as maximum values and are expressed in Ohms. A higher ESR requires the oscillator circuit to have larger negative resistance (at least 5x ESR) to ensure startup; this is affected by the gain and the load capacitance. Lower ESR requires a lower drive level and so results in lower power consumption. A lower ESR also means the oscillator starts up more easily.

- **LOAD CAPACITANCE (CL)**: The external load capacitance (C1, C2) must match the specified crystal CL to ensure the correct frequency of oscillation. A higher external load capacitance decreases the negative resistance of the oscillator and increases the startup time. If the load capacitance is too low, it can make the oscillator frequency more sensitive to stray capacitances and board layout. It also increases RF phase noise.

- **PULLABILITY**: The amount by which the crystal's oscillation frequency can be pulled from the natural resonance by changing the load capacitance. This is important for variable frequency oscillators.

CONCLUSIONS

RC oscillators are simple, but do not provide the accuracy and stability required by many applications.

Those requirements can be met using a crystal oscillator. Designing an oscillator from scratch can be complicated, but you can often use the oscillator built in to the device that requires the clock.

In other cases an off-the-shelf crystal oscillator module provides a simple solution. These are also available with higher accuracy and stability than integrated oscillators. If better temperature stability is required then temperature-compensated oscillators are also available.

For more information, please visit the Diodes Incorporated product pages:
www.diodes.com/products/connectivity-and-timing/clock-ics/