voltage must ensure that worst-case tolerances on supply voltage and zener voltage do not result in continuous conduction, and so the actual clamping voltage is inevitably higher than optimum (*cf* section 4.1.8). This is not usually a problem unless the breakdown voltage of the switch is already close to the supply voltage, which is bad practice anyway. The zener has the additional advantage of protecting the switch against transients on the supply rail. It can also be sized to achieve a compromise with respect to the turn-off time of the coil.

AC circuits

Both the diode and zener methods are only applicable when the supply is a polarised dc voltage. An ac coil requires a different protection method, and for this the snubber circuit Figure 3.25(c) is used. This essentially places an RC network in the path of the inductive current – the network can equally well be across the switch or the coil, provided the supply impedance is low – so that the current is absorbed by the action of charging C. The C is effectively in parallel with the self-capacitance of the coil which it swamps. The resistor limits the switch current when C is discharged at turn-on.

In this circuit, C should be sized carefully to ensure it is no greater than required to reduce the transient to a manageable level, since it slows down the response of the switch and also allows some current into the load when the switch is open. Similarly R should be kept as high as possible consistent with the snubbing action since power is lost both in it and in the switch, as C is discharged. The snubber is a popular network both for ac inductive clamping and in many other circuits as a dV/dt limiter. Calculation of snubber values is outlined in section 4.2.6.

3.5 Crystals and resonators

The quartz crystal has been widely used as a frequency-determining component for many years. It is small, robust, accurate and stable. Also, like other components, it has its vices. This section will look briefly at crystal theory before reviewing some application pitfalls, and also cover its cheaper but more popular cousin the ceramic resonator.

Quartz (silica, SiO_2) exhibits a piezoelectric effect whereby mechanical stress generates a directionally related electric field, and conversely an applied electric field causes a directionally related force across the crystal. An alternating voltage applied to the crystal will cause it to vibrate, and if its frequency is close to the mechanical resonance the generated electric field will be amplified and can be used to stabilise the applied frequency.

Angle of cut

The crystals used in electronic circuits are in the form of plates or elements cut from a synthetic crystal. The resonant properties vary depending on the angle of cut referred to the base crystal's major axis. X- and Y-cut units, where the direction of cut is perpendicular to the major axis, show subsidiary responses which can reduce the Q-factor of the element and impose a fairly low upper limit on the achievable frequency range. Also, the temperature coefficient of these cuts is large.

Happily, a particular angle of cut of 35° 21′ from the major axis known as the AT-cut, shows very small coupling between the principal and other modes of vibration, therefore lacks subsidiary resonances and is capable of very high-frequency operation. Its resonant frequency is governed directly by a fraction of the element thickness, and its temperature coefficient follows a cubic-plus-linear law whose actual slope varies according to the deviation of angle of cut (see Figure 3.29). The AT-cut crystal is the most widely available crystal unit for general purpose use. Other cuts are available for specialised applications.

3.5.1 Resonance

The crystal equivalent circuit is a series LCR tuned circuit together with a parallel

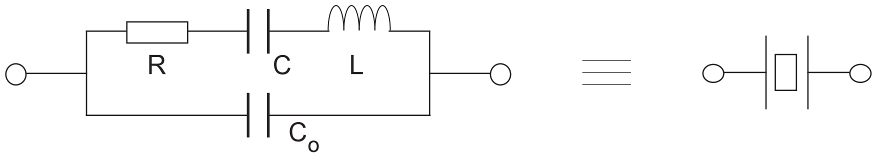

Figure 3.26 Crystal equivalent circuit

capacitance (Figure 3.26). C, L and R are functions of the mechanical resonance properties of the crystal element and C_o is the static capacitance due to the electrodes and terminations. C is very low (of the order of femto-farads) and L is very high (of the order of henries), while R is generally tens or hundreds of ohms for high-frequency units, and the Q of the resulting combination is very high (30,000–100,000). Because of this, the phase angle changes very rapidly with changes in frequency near resonance. So as an oscillator feedback component, the crystal will correct amplifier phase deviations with only a slight frequency shift.

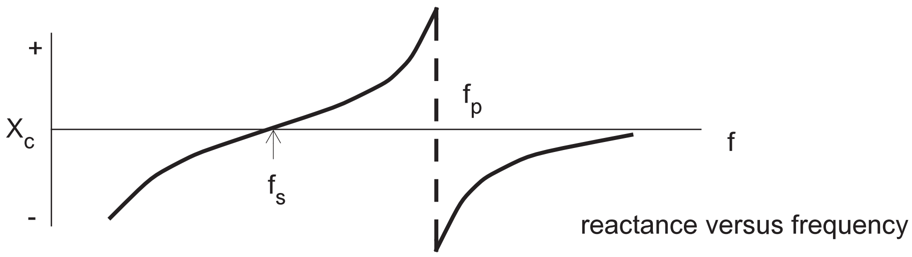

Figure 3.27 Series and parallel resonance

C_o is several hundred times larger than C, and is also increased by external circuit capacitance. The crystal shows two resonant modes, series and parallel, as Figure 3.27 indicates. Their resonant frequencies are very close together and are given by

$$f_s = 1/2\pi \cdot \sqrt{(L \cdot C)}$$

and

$$f_p = 1/2\pi \cdot \sqrt{(L \cdot C_x)}$$

where C_x is the series combination of C and C_p,
and $C_p = C_o$ + external capacitance

The crystal can be operated in either mode. In series mode, the element is operated at a low impedance which is equivalent to R; it can be "pulled" upwards in frequency slightly from f_s by inserting external series capacitance. In parallel mode the element operates at high impedance and can be pulled downwards in frequency from f_p by adding external parallel capacitance. The frequency shift from f_s in either case is the same for a given external capacitance. Clearly a given resonant frequency is only

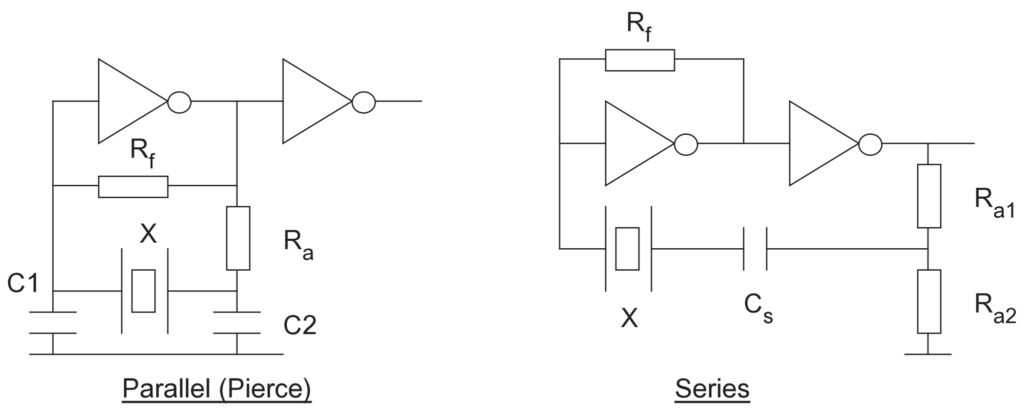

Figure 3.28 Typical crystal oscillators

obtainable if the external capacitance is known, and in fact all crystals are supplied for a quoted "load" capacitance. The unit will only operate at the marked frequency (within the given tolerance) if the actual circuit capacitance is as specified. Conversely, the frequency can be trimmed if absolute accuracy is needed by using a variable load capacitance.

3.5.2 Oscillator circuits

There are two common circuits for digital clock oscillators (Figure 3.28), one operating in each mode. The parallel circuit is only suitable for high-impedance (CMOS) devices while the series circuit can be used for high- or low-impedance devices. The parallel circuit can be run at very low power levels (down to 1µA) but is slow to start. It is commonly used by on-chip microprocessor clock oscillators and other CMOS oscillator/divider ICs, such as real time clocks.

R_f biases the inverter to linear operation and should be low enough for input bias current to have negligible effect but high enough not to load the crystal. Generally 10–15MΩ is reasonable. The crystal appears primarily inductive and provides 180° phase shift in the feedback loop. C1 and C2 in series together with circuit strays (amplifier input and pc track capacitance, amounting to at most 10pF with good layout) form the crystal load capacitance. The ratio C2:C1 should generally be of the order of 3:1, C2 being variable if frequency trimming is desired.

Drive level resistance

R_a is an important component and should not be omitted without proper consideration. It sets the drive level to the crystal. Too high a drive will lead to frequency instability and possible damage to the element. Too low a level will make the oscillator slow to start, perhaps impossible to start with low-activity units, and susceptible to interference. Typical AT-cut crystals have a maximum drive level of 0.5 to 1mW. Some circuits (for example low-power on-chip CMOS oscillators) have a high enough output impedance to make R_a unnecessary but this is not normally the case with discrete-gate oscillators. For watch-crystal units (32.768kHz) R_a should be tens or hundreds of kΩ.

Series circuit

Some applications may be embarrassed by the slow starting time (possibly up to 1 second) of the parallel oscillator circuit. Crystals have a very high Q and if the drive level is low, for frequency stability or to conserve current, the time taken to reach working level is appreciable. This may be unacceptable in microprocessor clock circuits where the clock is expected to be present immediately on power-up. For these purposes the series oscillator, in which the crystal is operated at a low impedance with minimal phase shift across it, is preferable. Its main disadvantage is its higher supply current. The same strictures on drive level apply. Note that the effective series resistance of the element, which is equivalent to its motional resistance R, can vary widely from unit to unit. A spread in this parameter of two- or three-to-one is not uncommon, so it is wise to design the circuit for assured start-up with a three times higher R than quoted.

Layout

Circuit board layout is important, particularly for the parallel mode. Extra capacitance across the crystal should be minimised, as this will increase loop gain and short-term stability. So should coupling between the oscillator circuit and other circuits, especially logic switching circuits, as this decreases the likelihood of spurious oscillation. Ground traces around the crystal to buffer other tracks are advisable; on no account route logic signals near or through the oscillator circuit as they will couple into the high-impedance nodes and cause frequency instability or jitter.

3.5.3 Temperature

Lastly, beware of temperature coefficients. The temperature law of the AT-cut is cubic (Figure 3.29) and if the cut angle is chosen carefully can be fairly flat at room temperature, but it worsens rapidly as the temperature limits are neared. A crystal will oscillate outside its rated temperature (usually) but the frequency stability will be impaired.

Tuning-fork crystals (the ubiquitous 32.768kHz type, universally used for real-time clocks) show a parabolic curve, of around -0.04ppm/°C^2. The turnover temperature is around 25°C which means that for digital watch applications, where the wrist temperature remains around this value, it is ideal and very stable. Transfer this type of crystal to an industrial real-time clock (for example) and its timekeeping at the extremes of the range is hopeless: at +85°C, and at –35°C, it is 144ppm low which represents a loss of 12 seconds per day. Be warned: use an AT-cut!

3.5.4 Ceramic resonators

A cheaper alternative to the quartz crystal is the ceramic resonator. This device uses the mechanical resonance of a piezoelectric ceramic, typically lead zirconate titanate (PZT), which vibrates in various mechanical modes depending on the chosen resonant frequency. The frequency ranges are approximately:

30kHz–1MHz:	longitudinal mode
100kHz–2MHz:	area mode
1MHz–10MHz:	shear thickness mode
2MHz–100MHz:	expansion thickness mode
10MHz–1GHz:	surface acoustic wave mode

The equivalent circuit of the resonator is identical to that of the quartz crystal (Figure 3.26) but the component values give it orders of magnitude lower Q. In terms of oscillation frequency accuracy, the resonator sits between the quartz crystal and the LC resonant circuit. The tempco of a resonator is of the order of 10^{-5}/°C compared to the better than 1ppm/°C achievable with quartz, and the 10^{-3} to 10^{-4}/°C of LC circuits. Its initial frequency tolerance is of the order of ±0.5% whereas quartz routinely achieves ±0.003%; to achieve these figures using LC circuits would need a trimming adjustment. On the other hand, the resonator is cheaper and smaller than quartz crystals and can use the same or similar oscillator circuits.

Load capacitors as in Figure 3.28 are necessary to prevent spurious oscillation modes and the manufacturer's recommendation for the oscillator circuit should be followed. A further advantage of the resonator is that because of its lower Q, the oscillation will start up more quickly than for an equivalent crystal circuit, which makes it attractive for applications which spend a lot of their time in "sleep" mode with the oscillator powered off.

All of these characteristics make the ceramic resonator the component of choice for frequency control of low- and mid-performance digital products, where a stable clock frequency is needed but where absolute accuracy or close control of tempco is not a requirement. It is mass produced and available in a wide range of standard frequencies, matched to particular consumer applications such as DTMF (telephone dialling tone) generators, remote control units and TV and audio systems.

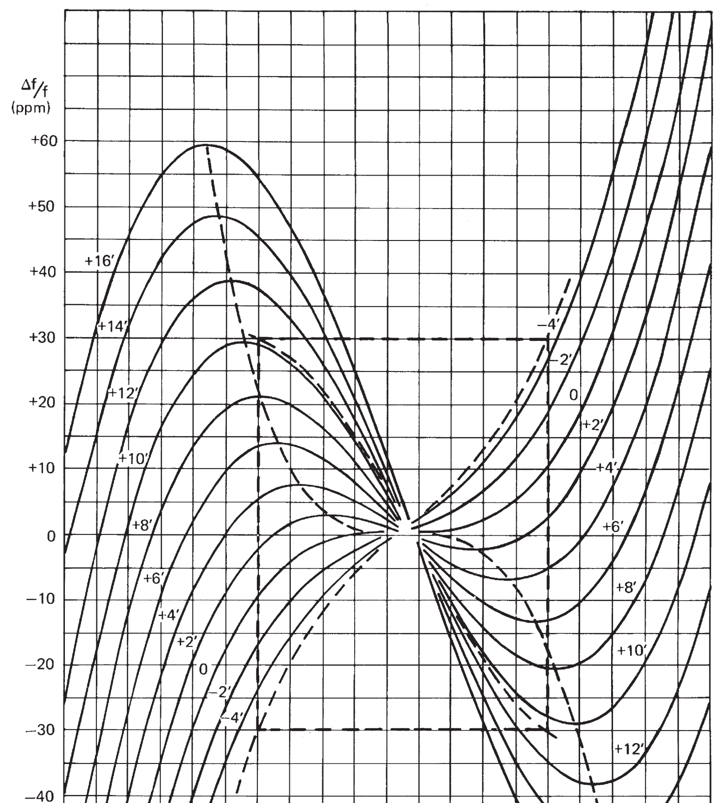

Figure 3.29 AT-cut frequency/temperature curves
Source: ECM Electronics