Quartz Crystals

An overview of these frequency controllers.

Hugh Wells W6WTU
1411 18th Street
Manhattan Beach CA 90266

Hams have been fascinated by quartz crystals since their first use. They and other people involved in radio have used quartz crystals for many years, perhaps without understanding the material.

Quartz has been recognized for at least 7,000 years and was originally used as jewelry. Around 1880 Professor Pierre Curie discovered the piezoelectric effect of quartz. This effect is the one used in radio crystals; it refers to the vibration of the crystal in the presence of an electric field.

Dr. Walter G. Cady took out a patent in 1920 on quartz as a means of controlling and measuring radio frequencies. At the time, most transmitters were self-excited and lacked frequency stability. With few stations and lots of frequency spectrum to work with, the instability was of little concern.

However, today it is another matter. Frequency stability and control are extremely important with the crowded bands. Quartz crystals have provided the means of controlling frequencies easily. Not too long ago, a radio required a crystal for every discrete frequency; today only one or two crystals are required in a frequency synthesizer to provide the stability required for all of the frequencies generated by the synthesizer.

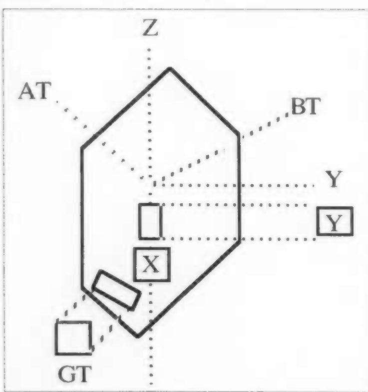

Fig. 1. Some of the different cuts available from a quartz bar.

Synthetic quartz

At one time, all of the quartz used for radio crystals was natural quartz material. Most of the world's supply of radio grade quartz was obtained from South America, and specifically from Brazil. But with a diminishing supply of high grade radio quartz and with increased demand, the development of synthetic quartz increased rapidly. Synthetic quartz, also called "cultured" quartz, was developed in 1845, even before piezoelectric effects were known.

Synthetic quartz is grown using hydrothermal techniques. Polycrystalline quartz is dissolved in a hot alkaline solution and then re-crystallized. Fragments of natural quartz are used as seed crystals to start the process by providing the model for crystalline structure growth from the solution.

The difference between natural and synthetic quartz is minimal as far as users are concerned, and usually involves imperfections in the crystalline structure of the synthetic material. These imperfections are detected and discarded at the time of material grading, before making usable radio crystals.

It is interesting to note that the structure of synthetic quartz is considerably more uniform than natural quartz. The purity of synthetic quartz has provided a higher yield of radio grade quartz than was ever obtained from natural quartz. The final result is a lower cost to the user.

When a crystal is ordered from the factory, the user seldom knows much more than whether the crystal is a fundamental or overtone type. **Fig. 1** shows some of the different cuts from the quartz bar. Each of the cuts has a name, such as AT, BT, CT, GT, etc. The various cuts exhibit different characteristics, which crystal manufacturers take advantage of to produce a crystal suitable for each application.

The crystal bar has three main axes, X, Y and Z. These axes are really directions and are related to the physical property of the material (**Fig. 2**). The Z axis is the easiest to identify because it runs the long way from end to end of the bar. The X axis runs in a direction through the corners of the bar and 90 degrees from the Z axis. The Y axis is a direction through the flat side of the bar and 90 degrees from both the X and Z axes. All of the specific crystal cuts are oriented from these axes.

Quartz use applications

The first usable cuts made from a quartz bar were from the X axis. Later the Y cut was introduced because it was easier to excite in an oscillator circuit than an X cut. However, the Y cut stability tended to be poor and it could change frequency abruptly. During World War II, crystal cuts such as AT, BT and CT were developed to reduce the effects of

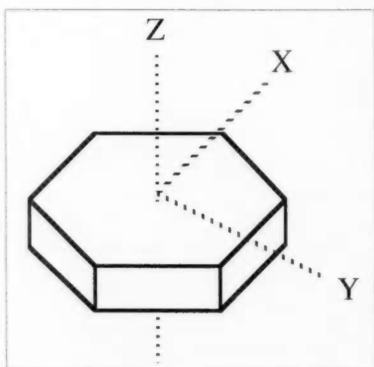

Fig. 2. Quartz bar slice, showing the X, Y and Z axes.

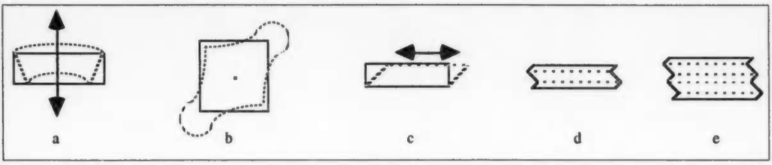

Fig. 3. ***Relative frequency range and mechanical movement:*** *(a) Fundamental flexure mode 10 kHz - 100 kHz. (b) Fundamental face shear 180 kHz - 1 MHz. (c) Fundamental thickness shear 1 - 20 MHz. (d) 3rd overtone 5 - 61 MHz. (e) 5th overtone 50 - 125 MHz.*

temperature and abrupt shifts in frequency. The AT cut is now the most popular for radio applications, but BT, CT and GT cuts are used extensively to meet stability and overtone requirements as a function of temperature and excitation.

A quartz crystal is cut with a saw running in a slurry containing diamond dust. Originally only one saw blade was used, allowing one crystal blank to be cut at a time. Now, a gang saw is used so that many crystal blanks can be cut in a single pass. Once cut, each blank is graded and finished to customer requirements.

Quartz responds to the effects of an electrical field by creating a mechanical movement (piezoelectric). The relative frequency range and mechanical movement are shown in **Fig. 3**. Fundamental low frequency crystals with their large mass vibrate to create the appearance of a pillow. At higher fundamental frequencies, the crystal appears to squirm (rotate about its center line). During overtone operation, the crystal appears to vibrate in shear. The number of shear layers produced are odd in number; that three layers produce the third overtone (third harmonic of the fundamental). Five layers would produce the fifth overtone, etc. The overtone frequency produced, although not controlled by the fundamental mode, is a near multiple of the fundamental (about 25 kHz per overtone higher). When being produced, the crystal is processed for the end use frequency and overtone mode of operation with no concern as to what fundamental properties it might have.

In operation, the quartz crystal functions just like a coil and capacitor in a resonant circuit and can function as either a series or parallel resonant circuit. Fig. **4** shows the equivalent circuit of a crystal which can be used to define the operation of the crystal exactly. The inductance L represents the mass of the crystal, the capacitance C1 represents the resilience, and the resistance R represents the frictional losses. Capacitor C2 represents the crystal electrodes across the crystal as a dielectric. Capacitor C3 represents the series capacitance of the crystal and the electrodes. Depending upon the mode, the circuit can represent either a series or parallel resonant circuit. When the combined reactance of C1 and L are inductive and equal to the reactance of C2, the crystal will operate in the anti-resonant mode (parallel resonance). When the reactance value of L equals C1, the crystal will operate in the resonant mode (series resonance).

When operating a crystal in an oscillator circuit, capacitor C2 may be paralleled with a trimmer capacitor to cause a small change in the crystal's anti-resonant frequency. If the crystal is operating in the overtone mode, either series inductance or capacitance will cause a crystal frequency shift. External frequency adjustment must be used sparingly as crystal stability will be affected. **Fig. 5** shows the reactance curve of a quartz crystal and the small difference between the resonant and anti-resonant points. Notice that the resonant (series) frequency is slightly lower than anti-resonance (parallel). In the resonant mode, the crystal exhibits a low impedance across its terminals, and a high impedance across its terminals when in anti-resonance.

One of the biggest user concerns about quartz crystals is the aging factor. In other words, how much will the crystal drift after it is placed in operation? Quartz crystal aging applies to the cumulative change in frequency, which results in a permanent change in the operating frequency. The rate of change is the fastest during the first 45 days of operation. Many interrelated factors are involved in aging, some of the most common being internal contamination, excessive drive, surface change of the crystal, various thermal effects, wire

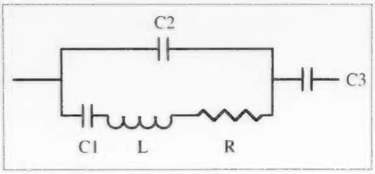

Fig. 4. Equivalent circuit of a crystal which can be used to exactly define the operation of the crystal.

fatigue and functional wear. Proper circuit design incorporating low operating ambients, minimum drive level and static pre-aging will greatly reduce all but the most severe aging problems.

Vibration

Quartz crystals vibrate when operating due to their piezoelectric characteristic, although the amount of vibration is quite small in relation to the physical size of the crystal. Even though small, the vibration causes stresses in the structure, which generates heat. If not kept within limit, the internal stress can cause permanent damage through rapid aging and/or fracturing. Excessive oscillator drive can cause severe stresses to occur. Once fractured, of course, the crystal is no longer of any value.

Vibration of the crystal also creates heat which can adversely affect the operation and stability of the crystal. Frequency drift is the usual symptom of heat. To keep the crystal temperature down, the oscillator drive level must be kept as low as possible, usually below 1 mW for crystals used as a standard frequency reference. Overtone crystals may require 1-2 mW of drive, while fundamental crystals operating below 10 MHz may require up to 10 mW. The drive level should be cut by 50% of the above indicated values when the crystal is used in an oven.

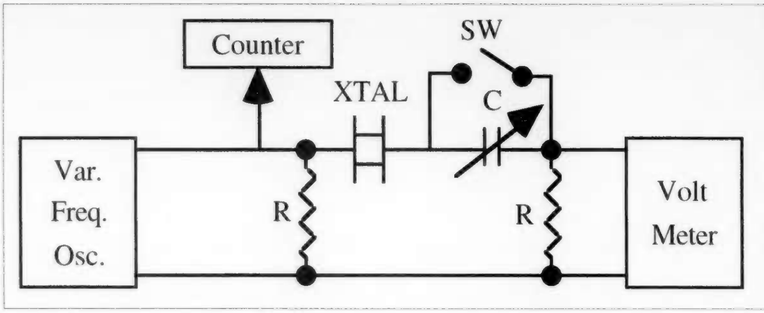

Fig. 6. Crystal test circuit.

The amount of crystal drive is usually related to the amount of crystal activity required, and in this case refers to the ability of the crystal to vibrate. Some crystal test oscillators have a meter in the circuit to indicate the relative strength of activity. The amount of crystal activity indicated by a meter is vague, but nevertheless provides a reference.

Many things control the amount of activity that a crystal will exhibit. For the older style pressure-mounted crystals, dirt and mounting conditions were a major factor. Modern hermetically sealed crystals are not affected by the environment. Therefore, manufacturing techniques, the Q factor of the cut and frequency will affect the drive level requirement. Of importance, though, is the ability of the crystal to start easily in the circuit and maintain a given frequency. The amount of drive applied should be just high enough to create reliable oscillator stability and operation. A large drive value could cause fracturing or excessive aging.

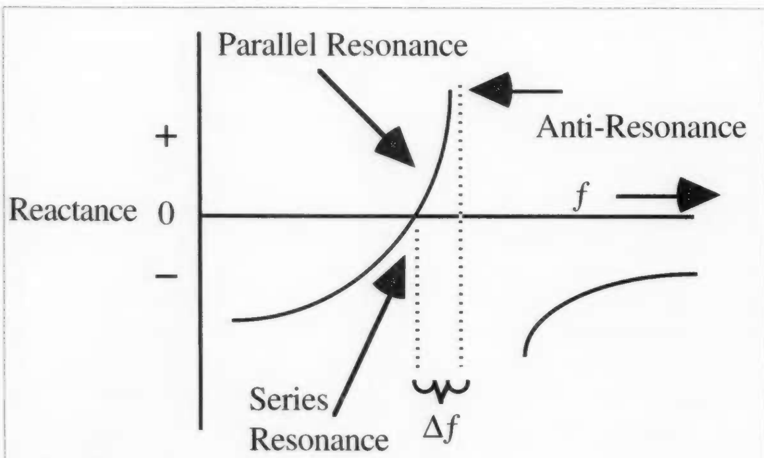

Fig. 5. The reactance curve of a quartz crystal.

Testing a crystal

Parameters of a quartz crystal can be tested by placing the crystal into a passive network, as shown in **Fig. 6**. A variable frequency oscillator is used to drive the crystal, which is mounted in a pi network of equal value non-inductive resistors. An RF voltmeter is placed on the output to measure the signal transferred through the network. For phase angle measurements, a vector voltmeter may be placed in parallel with the crystal. Being passive, the crystal will respond to the drive frequency at both its resonant and anti-resonant frequencies. Actually, the crystal operates/responds as a filter. Using this network, it is possible to measure the phase angle of the voltage across the crystal (zero degrees equals resonance, 180 degrees equals anti-resonance), determine the crystal impedance and equivalent resistance and determine the crystal's load capacitance. The load capacitance can be determined by placing a capacitor in series with the crystal while it is connected in the network and then measuring the voltage vector across it. As an example, the frequency of the oscillator is set to the anti-resonance frequency of the crystal (180 degrees of phase shift across the crystal), then the value of the series capacitor is adjusted until a phase angle of 180 degrees is obtained across it. The total phase angle between the oscillator and network output is 360 degrees. The value of the series capacitor is equivalent to the load capacitance value (typical values range from 20 to 32 pF).

Not all of the parameters are needed to use the crystal in an oscillator; but the more that are known, the simpler it is to design the oscillator. 73