The *Lenkurt*

DEMODULATOR

NOVEMBER 1970

crystal filters ○ part one

Improved carrier design has followed closely on the heels of filter development. Crystal filter design has recently improved quality and reduced size of carrier and multiplex systems.

Filters have played such an important role in carrier communications that it is worth discussing their history and development, with an emphasis on crystal filters. The technique of carrier and multiplex system design points out the filter requirements and the need for certain types of filters.

Analogies are often used to describe filters, but comparing electronic filters to such things as a screen, a strainer, or a piece of paper used to separate solids and liquids may be misleading. A filter placed in an alternating current transmission path permits the free passage of certain frequencies and blocks others. The degree to which the filter blocks (attenuates) the signal is a function of the filter design and is measured in decibels.

Resonance

The principle that allows a filter to discriminate between frequencies, passing some while rejecting others, is known as resonance. The reeds and strings of musical instruments exhibit this natural phenomenon of resonance – the desire to vibrate at a single frequency. Filter operation can be explained using the principle of resonance and the analogy of a child jumping rope. If the child is jumping at the same frequency that the rope is turning, the child can jump into, with, and out of the turning rope with little difficulty. If, on the other hand, the child is not jumping at the rope's frequency, there will be interference and the child will not be able to pass through the turning rope.

Perhaps this analogy belabors the point, but it is important to understand the relationship between resonance and filter operation. An ac signal at the resonant frequency of the filter will be passed through the filter and other frequencies will be attenuated. If this analogy were to hold exactly, the characteristic curve of such a filter would look like Figure 1.

Electronic filters, however, do not fit this single-frequency characteristic curve, but rather have varying degrees

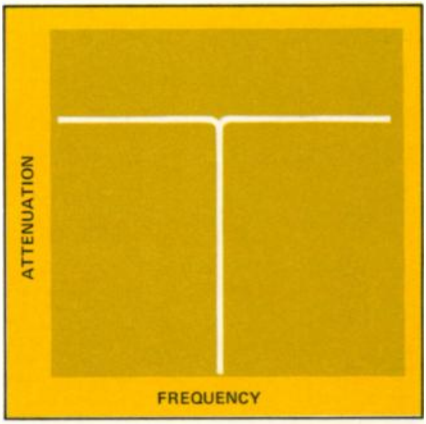

Figure 1. A filter that blocks all except its resonant frequency would have a characteristic curve as shown.

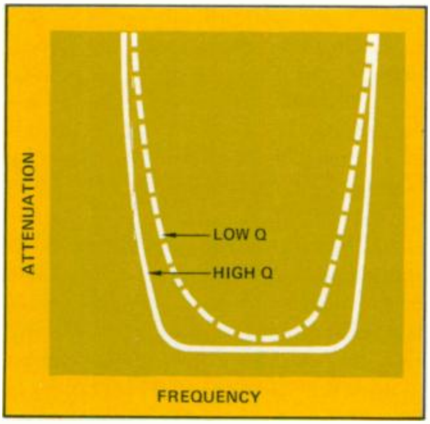

Figure 2. These curves show the passbands of the same filter made with resonators having different Q values. Note that high Q values must be used if the filter is to have a flat passband with sharp corners.

of sharpness, and actually pass a range of frequencies. This spreading of the pass region is a function of the filter resistance.

The term used in filter language to describe resonator sharpness is Q, which is inversely proportional to the resistance. High Q's indicate low resistance, high efficiency, and the ability of resonant circuits to obtain sharp, steep discrimination. Conversely, low Q's indicate a lack of sharpness. Figure 2 shows what happens to the passband response of a filter built with either low Q or high Q resonators. The actual Q value required will be determined by the bandwidth of the filter and also by its approximate center frequency. For example a bandpass filter having a 4-kHz passband will require lower resonator Q's to give the same flat passband if it is built at a center frequency of 10 kHz than if its center frequency is 10 MHz.

Bandpass Filters

An interesting point worth remembering is that not all resonant circuits are considered to be filters; however, all filters are combinations of resonant circuits. The art of designing filters involves using a number of resonant elements properly coupled together so that zero attenuation is approximated at all frequencies in the desired passband and maximum attenuation is achieved at all other frequencies. Figure 3 shows a typical LC filter as a series of LC resonators.

The low Q of early LC filters motivated Lenkurt, and others, to devel-

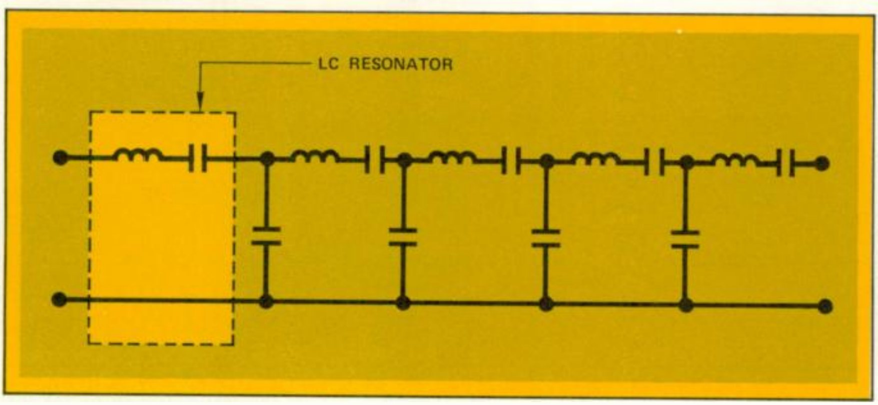

Figure 3. A typical LC filter is made up of a series of LC resonators.

op magnetic cores from powdered metals for low resistance inductors to improve LC filter sharpness. The rounded corners at the ends of the passband were eventually squared off by developing inductors with increasingly lower resistance ratings. It is still not possible to obtain stable inductors with Q's much greater than 500. Therefore, the center frequency of an LC filter for a 4-kHz wide voice channel is confined to values less than 100 kHz.

Early Crystal Filters

LC networks are not the only type filters capable of separating channels in carrier systems. Crystal filters are just as suitable and perform even better. Rather than using electrical components to form a resonant circuit, certain crystalline materials can be set in mechanical resonance by an electrical field. Such crystalline material is called piezoelectric and is such that mechanical vibrations can be excited in the crystal by ac signals.

A crystal resonator is simply a plate of piezoelectric material, usually quartz, with a metal electrode on each side of the plate. If these two electrodes are connected to an alternating current, the crystal will try to vibrate at the signal's frequency. And, if the crystal has been cut to the proper dimensions, it will be set in resonance by the signal.

The passband for crystal filters has steep sides and square corners. This sharpness of a crystal filter is the result of the higher Q's of the crystal resonators that comprise the filter. Q, the ratio of reactance to resistance, can be increased by lowering the resistance, as was done with early LC resonators, or by raising the effective reactance. A crystal resonator with the same resonant frequency as an LC resonator has essentially the same inherent resistance. But the effective inductance and capacitance of the crystal resonator differ in such a way that the reactance of the crystal resonator is much larger – resulting in a larger Q. Figure 4 shows typical values for an LC resonator and a crystal resonator designed for the same resonant frequency.

Crystal filters appear to be far superior to LC filters, yet crystal

	LC resonator	Crystal resonator
Frequency	10 MHz	10 MHz
Inductance	.01 mH	9.2 mH
Capacitance	25 pF	.028 pF
Resistance	4 ohms	3.8 ohms
Q	157	152,000

Figure 4. The table shows the equivalent values for an LC resonator and a crystal resonator operating in the same frequency range.

filters were not used in early carrier systems since performance is not the only criterion in filter selection. Since LC filters were improved to give satisfactory performance, the use of costly, bulky, high Q crystal filters could not be justified.

Changing Requirements

Cost and size reduction are being stressed in this age of miniaturization. Therefore, the high cost and large size of low-frequency crystal filters make them even more unsuitable for miniaturized carrier equipment. But, for reasonable performance, at least at frequencies below several megahertz, inductors for LC filters also require a volume incompatible with present-day miniaturization.

The size of the quartz plates used in crystal resonators, and consequently, the filters themselves can be reduced by increasing the frequency at which the signal is filtered. The resonant frequency of a quartz plate is inversely proportional to the plate size; therefore, the smaller the plate, the higher the frequency. The upper limit on the resonant frequency of a crystal is determined by the smallest plate that can be easily handled and will not shatter at the resonant frequency.

From this it seemed logical that one way to reduce the size of crystal filters was to design a carrier system that filters higher frequencies – designing the carrier system around the filter. A small, inexpensive, high-frequency crystal filter had to be developed before the new carrier system could be designed.

Crystal size is the limiting factor in resonant frequencies but the mode of vibration is also a determining factor. The vibration mode – whether flexure, extensional, face shear, or thickness shear – is determined by the crystal cut.

High-Frequency Filters

The cut considered for high-frequency crystal filters is the AT cut because it exhibits good frequency stability, as shown in Figure 5. The cut of the crystal determines the angle at which the plate (or wafer) is cut from the block of raw crystalline material and has nothing to do with the size of the crystal. Therefore, an AT cut crystal can come in a variety of sizes and consequently, a variety of resonant frequencies.

High-frequency AT cut crystals vibrate in a thickness shear mode. In this mode the surfaces under the electrodes move in opposite directions with both surfaces remaining parallel. Figure 6 illustrates the thickness shear mode of vibration.

In the thickness shear mode of vibration other modes and overtones of the fundamental resonant frequency can also be excited. In this case, experience has shown that rather than eliminating these unwanted modes and resonances, reduction of their intensity will accomplish the same results.

Energy Trapping

As early as 1946, methods of eliminating unwanted modes of vibration were being studied. W. S. Mortley published an article in 1946 on his experimental observations of what has since become known as energy trapping. Mortley's theory was given little attention when it was first published. It was not until the early 1960's that his original work began to have relevance and was given the proper attention in crystal filter design.

Prior to Mortley's experimentation, unwanted modes of vibration were eliminated by thinning the crystal plate toward the edges. This had the effect of reducing the intensity of all modes except the desired thickness

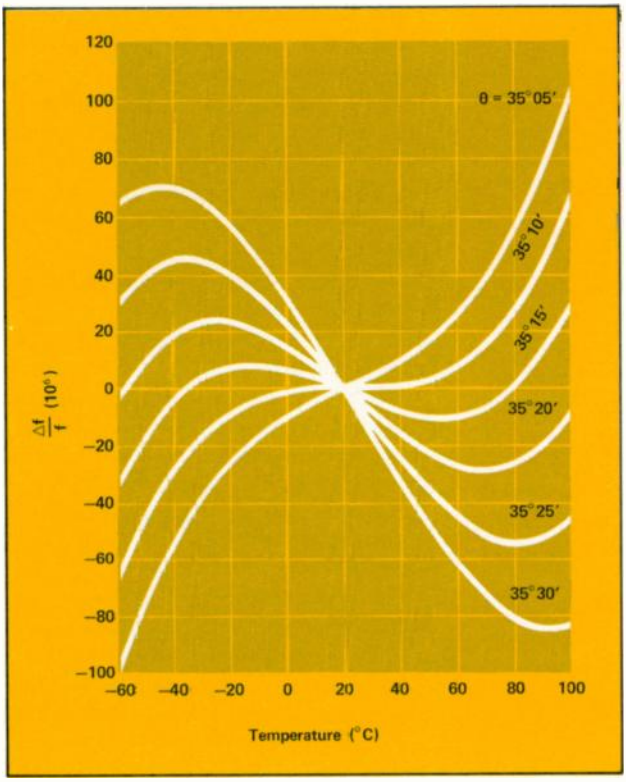

Figure 5. An AT cut crystal with an angle of 35° 10' has the best frequency stability.

shear mode. By reducing these unwanted modes, interference between them was avoided. This technique of thinning the crystal is known as shaping and works well in crystal resonators where there is an air-gap between the crystal plate and the electrodes. Mortley noticed, however, that shaping was not a successful technique for eliminating unwanted modes of vibration in crystals with deposited metal-film electrodes.

The reappearance of unwanted modes with deposited metal-film electrodes led Mortley to conduct some further experiments. From these he discovered that the intensity of some unwanted modes and also their frequency spacing with respect to the desired mode could be controlled by the mass of metal in the film and the shape of the electrodes.

From these observations it was suggested that the same laws that apply to the propagation of electromagnetic waves apply equally well to the transmission of mechanical shear waves in quartz.

The comparison of mechanical shear waves in quartz to electromagnetic wave propagation was carried even further. The filter can be compared to a waveguide. Just as it is possible to have a high coefficient of reflection from the junction of waveguides differing slightly in dimensions, quartz crystal also reflects waves where the crystal changes shape. Therefore, by putting the proper step in the crystal in the direction of wave

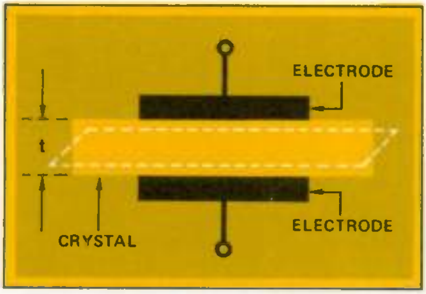

Figure 6. The dotted line shows the thickness shear mode of vibration in an AT cut crystal.

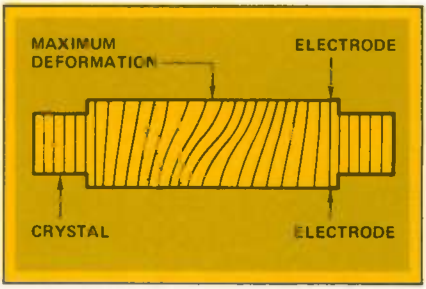

Figure 7. The shear waves are trapped in the thicker area under the electrodes.

propagation it is possible to trap the desired modes of vibration. Figure 7 shows the effect of dimensional changes on wave propagation.

For high-frequency filters, where the crystal is small and fragile, it is not practical to machine steps in the quartz. Crystal filters with metal-film electrodes deposited on a flat crystal plate have an inherent step. The metal-film on the outer surface of the crystal adds to the vibrating mass of the quartz plate, trapping the energy under the electrodes, because the boundary of the electrode acts like a dimensional step in the quartz plate. Those unwanted modes and resonances travel into the thinner unplated areas where they decay exponentially with distance.

Although Mortley had proposed this theory of energy trapping, the actual control of unwanted modes was more of an art than a science for many years after Mortley's paper. Bechmann in 1961 published a set of experimentally derived rules which give optimum dimensional ratios for the crystal plate and the electrodes to suppress the unwanted modes. In 1963 Shockley, Curran, and Koneval formulated their theory of energy trapping which was essentially the same as Mortley's and which confirmed Bechmann's experimentally derived numbers.

New Horizons

The theory of energy trapping has opened up a whole new area for high-frequency crystal filter design. This theory has led to the design of filters where multiple resonators are placed on a single quartz plate.

Crystal filter techniques have come a long way from the first high-cost, low-frequency, bulky designs rejected for carrier channel usage. Today multi-resonator crystal filters are responsible for reduced size and cost of improved carrier systems. These new multi-resonator crystal filters and their effect on carrier and multiplex system design will be the subject of the next DEMODULATOR.

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