CHAPTER 10.5

CRYSTAL, MECHANICAL, AND ACOUSTIC COUPLED-RESONATOR FILTERS

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In applications such as single-sideband communications it is often necessary to have a bandpass filter with a bandwidth that is a fractional percentage of the center frequency and in which one or both transition regions are very short. Meeting such requirements usually requires a filter in which the resonators are not electrical. Two types of resonator are quartz crystals and mechanical elements, such as disks or rods. Transducers from the electric signal to the mechanical device, output transducers, and resonator-coupling elements are needed.

Crystal filters include resonators made from piezoelectric quartz crystals. The transducers are plates of a conductor deposited on the appropriate surfaces of the crystal, and coupling from one crystal to the next is electrical. The center frequency depends on the size of the crystal, its manner of cutting, and the choice of frequency determining modes of oscillation. It can vary from about 1.0 kHz to 100 MHz. If extreme care is taken, equivalent quality factors (Q's) can be greater than 100,000. These filters can also be very stable with regard to temperature and age.

Mechanical filters use rods or disks as resonating elements, which are coupled together mechanically, usually with wires welded to the resonators. The transducers are magnetostrictive. The frequency range varies from as low as 100 Hz to above 500 kHz. Quality factors above 20,000 are possible and, with proper choice of alloys, temperature coefficients of as low as 1.0 ppm/°C are possible.

Acoustic filters use a combination of crystal and mechanical filter principles. The resonators are monolithic quartz crystals; the transducers are similar to those of crystal filters, but the coupling is mechanical (referred to as acoustic coupling). These filters have many of the properties of crystal filters, but the design techniques have much in common with those of mechanical filters.

Coupled-resonator filters are usually described in terms of an electric equivalent circuit. The direct or mobility analogy (mass to capacitance, friction to conductance, and springs to inductance) is more useful, because the "across" variables of velocity and voltage are analogous, as are the "through" variables of force and current. Equivalent capacitances or inductances and center frequencies are among the common parameters specified for filter elements.

The following paragraphs discuss, in general terms, the design procedure used for coupled-resonator filters, the equivalent circuits used, and some network transformations that enable the designer to implement the design procedure. References 6, 8, and 27 give much additional information, and in particular, Ref. 27 contains an extensive discussion and bibliography. Manufacturer's catalogs are a good source of current data.

COUPLED-RESONATOR DESIGN PROCEDURE

The insertion-loss low-pass prototype filters can be used to design coupled-resonator bandpass filters. Five steps can be identified in the process, though in some cases the dividing lines become indistinct.

1. Transform the bandpass specifications to a low-pass prototype, using Eq. (8). This will take the center frequency to $\omega = 0$ and, usually, the band edge to $\omega = 1$.
2. Choose the appropriate low-pass response, e.g., Chebyshev, elliptic, or Butterworth, that meets the transformed specifications. Zeros of transmission are fixed at this time. From this characteristic function determine the transfer function that is needed. The tables presented earlier may be useful.
3. Determine the short-circuit y or open-circuit z parameters from the transfer function.
4. If possible, look up or synthesize the appropriate ladder or lattice network needed. At this point, it is still a low-pass prototype. The technique chosen may depend on the expected form of the final network.
5. Use Fig. 10.2.7 to transform the network into a bandpass network and then use network theorems to adjust the network to a configuration and a set of element values that is practical, i.e., one that matches the resonators.

This process is not one in which success is assured. It may require a variety of attempts before a suitable design is achieved. Equivalent circuits and network theorems are summarized in the following paragraphs.

EQUIVALENT CIRCUITS

The most common equivalent circuit for a piezoelectric crystal shows a series-resonant *RLC* circuit in parallel with a second capacitor, as shown in Fig. 10.5.1. The parallel capacitor C_P is composed of the mounting hardware and electric plates on the crystal. In practice, the ratio C_p/C cannot be reduced below about 125, but it may be increased if needed. When a filter contains more than one crystal, the coupling is electrical, usually with capacitors.

Mechanical filters have an equivalent circuit, as indicated in Fig. 10.5.2. The resonant circuits L_0, C_R represent the transducer magnetostrictive coils and their tuning capacitances. (In cases of small R_L, it may be more accurate to place C_R in series with L_0.) The resonant circuit L_1, C_1, R_1 and L_n, C_n, R_n include the motional parameters of the transducers. Elements L_2, C_2, R_2, . . . , L_{n-1}, C_{n-1}, R_{n-1} represent the motional parameters of the resonant elements, and L_{12}, . . . , $L_{n-1,n}$ represent the compliances of the coupling wires.

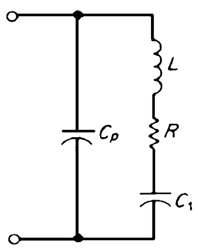

FIGURE 10.5.1 Equivalent circuit for piezoelectric crystal. Because coupling is electrical, a one-port representation is sufficient.

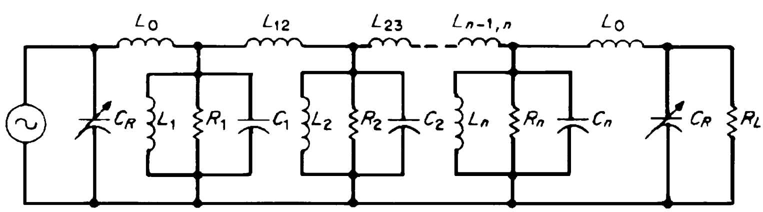

FIGURE 10.5.2 Equivalent circuit for a mechanical filter. A two-port representation allows an electric equivalent circuit for the entire filter.

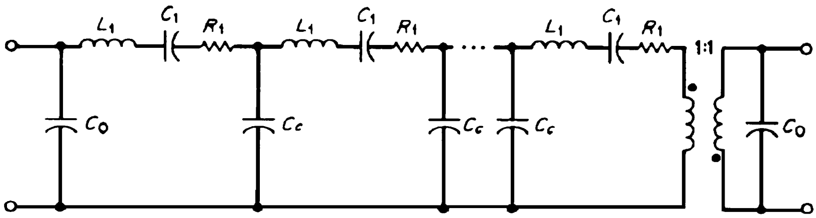

FIGURE 10.5.3 Equivalent circuit for a monolithic crystal or acoustic filter. The one-to-one ideal transformer models the 180° phase shift observed in these filters.

The acoustic filter is represented, after substantial development, by the circuit shown in Fig. 10.5.3. The development has made the circuit easy to use, but the association between the electrical elements and the filter elements is less apparent than in the previous circuits. The ideal transformer at the output accounts for the 180° phase shift observed in these filters. In some analyses, it may be omitted.

NETWORK TRANSFORMATIONS

In the process of changing a bandpass circuit to meet the configuration of the equivalent circuit of a coupled resonator a variety of equivalent networks may be useful. At one step negative elements may appear. These can be absorbed later in series or parallel with positive elements so that the overall result is positive.

The impedance inverters of Fig. 10.5.4 can be used to invert an impedance, as indicated. Over a very narrow frequency range they can often be approximated with three capacitors, two of which are negative. An inverter can be used to convert an inductance into a capacitance provided the negative elements can then be absorbed. Other similar reactive configurations can also be used.

Lattice networks (Fig. 10.5.5) are often used in crystal filters. If the condition prevailing in Fig. 10.5.6 exists, the equivalent can be used in either direction to affect a change. In particular, the ladder can be transformed into a lattice, which then has the crystal equivalent circuit.

Two Norton transformations and networks derived from them are shown in Figs. 10.5.7 and 10.5.8. They lead to negative elements, and it is expected that they will later be absorbed into positive elements. Humphreys[8] gives another derived Norton transformation that can be used to reduce inductance values. It changes the impedance level on one side of the network. When this is applied to a symmetrical network, the new impedance levels will eventually become directly connected, so that no transformer is needed.

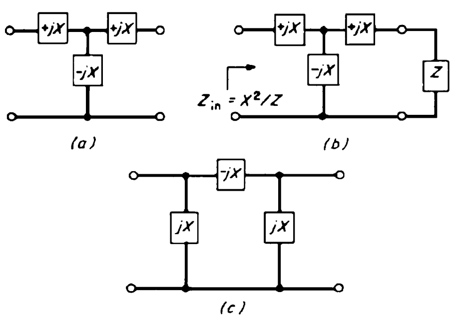

FIGURE 10.5.4 Reactive impedance inverters: (*a*) *T* inverter; (*b*) *T* inverter with load *Z*; $Z_{in} = X^2/Z$; (*c*) π inverter.

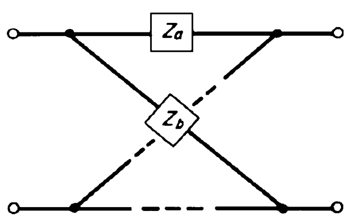

FIGURE 10.5.5 Symmetrical lattice. The dotted diagonal line indicates a second Z_b; the dotted horizontal line, a second Z_a.

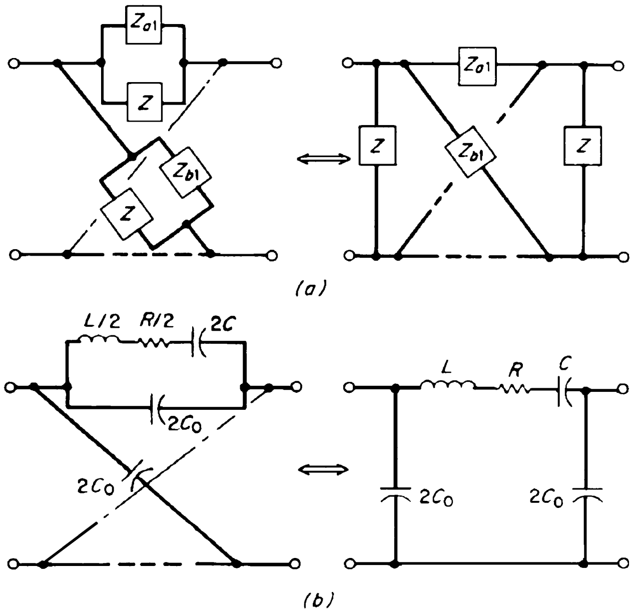

FIGURE 10.5.6 Lattice and ladder: (*a*) general lattice and equivalent circuit; (*b*) application to crystal filters.

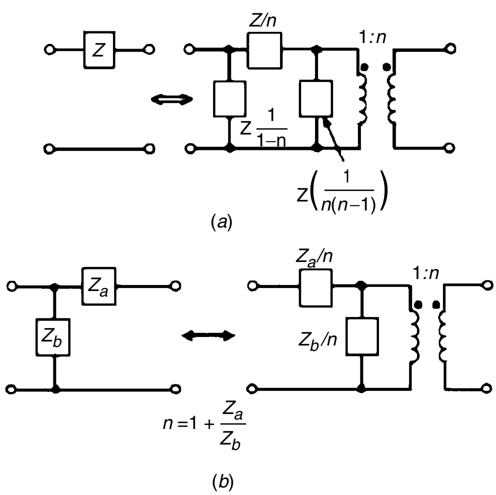

FIGURE 10.5.7 Norton's first transformation and a derived network.

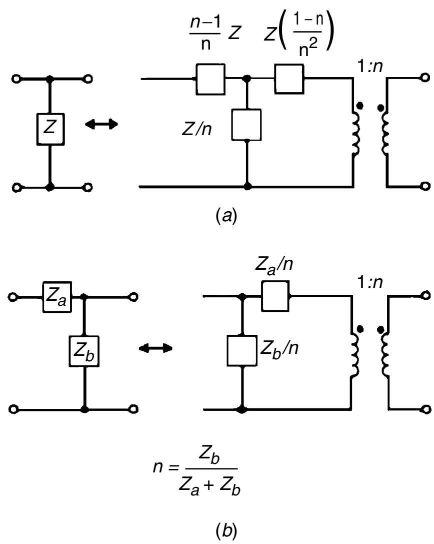

FIGURE 10.5.8 Norton's second transformation and a derived network.