8 Measurements

8.1 INTRODUCTION

The quantities to be measured in the determination of the performance of a crystal resonator are the frequency of the resonator under the specified operating conditions, its motional resistance and, optionally, the values of the motional parameters L_1 and C_1 and the shunt capacitance C_0. It may, in addition, be necessary to determine the location and level of unwanted modes. Some or all of these measurements may need to be repeated to determine the variation of selected parameters with such factors as temperature, time and drive level. The range of values of the parameters involved is such that until very recently it was necessary to use measurement techniques and instruments specifically tailored to quartz resonators, but the present day availability of computer controlled test equipment has made it feasible to use standard instruments such as network analysers for crystal measurements.

The methods used for crystal measurements fall into four groups, based, respectively, on crystal impedance meters, bridge techniques, transmission networks, and automated measuring systems. A full review of all these methods is provided by Hafner in Gerber and Ballato (1985), so the discussion here will be limited to a brief outline of the commonly used techniques and of the possibilities offered by the new automated systems.

8.2 CI METERS

The CI meter or *crystal impedance* meter is essentially a crystal-controlled oscillator designed to operate at series resonance, either with or without a series load capacitor. Figure 8.1 shows a simplified block diagram in which the crystal appears in the series arm of a feedback network. The principle of measurement is to find by repeated substitutions and adjustments of the oscillator tuning, a resistor R and a frequency f such that the signal level and frequency are unchanged by substitution of the crystal by the resistor. The series resonance frequency of the crystal and its resistance at that frequency are then precisely f and R.

In practice, the substitution process is very laborious, and is short-circuited by arbitrarily selecting a resistor close to the anticipated crystal resistance and

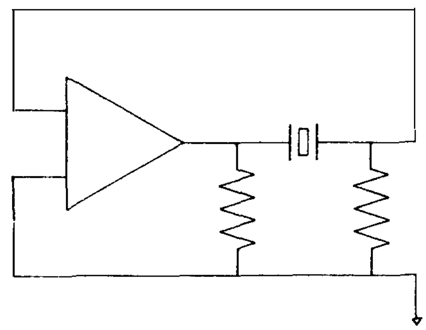


Fig. 8.1 CI meter schematic.

tuning the CI meter to the nominal crystal frequency with this resistor in circuit. The crystal is then substituted for the resistor and the oscillator frequency taken as the crystal frequency. Clearly this method is not so accurate as the full substitution method, although quick and convenient for most practical purposes. Even assuming the full procedure is used, the CI meter still has disadvantages that have resulted in the IEC adopting as a standard a measurement technique based on the use of a transmission network.

8.3 ZERO PHASE MEASUREMENT SYSTEMS

Figure 8.2 shows a block diagram of the basic method adopted by the IEC as an international standard for crystal measurements in the frequency range up to 125 MHz. The method is fully described in IEC Publication 444 (IEC, 1973), the key element in the system being the pi-network, whose schematic is

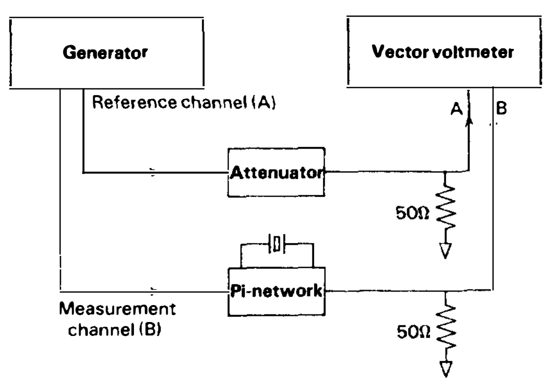
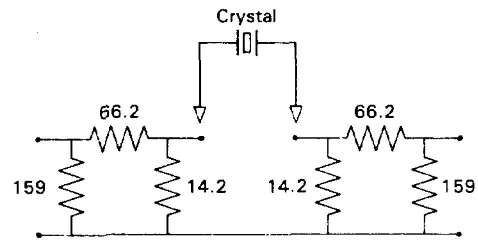


Fig. 8.2 Zero phase measuring system.



Resistor values in Ω

Fig. 8.3 Pi-network schematic.

shown in Fig. 8.3. The pi-network is designed so as to present to the crystal unit precisely defined low impedances of 12.5 ohms, and at the same time to match to standard 50 ohm coaxial cables. When the crystal is replaced by a short-circuit, the pi-network has a loss of 29.6 dB between 50 ohm terminations, and to ensure that the reference and test channels present signals at approximately the same level to the vector voltmeter, an attenuator of approximately this value is placed in the reference channel. As with the CI meter, the zero phase method is in principle a substitution method. A reference resistor is used to set zero phase at the nominal frequency, and is then replaced by the crystal. The generator frequency is then adjusted (manually or often automatically) until the zero phase condition is restored, and the set frequency taken to be the zero phase frequency of the crystal unit. The resistance of the crystal can be calculated from the ratio of the test-channel voltage V_B with the crystal in circuit to the corresponding voltage V_{BS} with the crystal replaced by a short-circuit

$$R = 25\{(V_{BS}/V_B) - 1\} \tag{8.1}$$

The highest accuracy for the frequency measurement is obtained when the reference resistor used has the same value as the crystal resistance, but in any event, the accuracy of the zero phase method depends crucially on the construction of the reference resistors and the pi-network itself.

As in CI meter measurements, the determination of the motional parameters requires several frequency measurements to be made under different conditions, with the parameter values following by calculation. For example, if measurements are made of the load resonance frequencies f_A and f_B corresponding to load capacitors C_A and C_B, the motional capacitance C_1 is given by

$$C_1 = 2(C_A - C_B)(f_B - f_S)(f_A - f_S)/f_s(f_B - f_A) \tag{8.2}$$

where C_0 and f_s are the static capacitance and series resonance frequency respectively. Alternatively, if IEC Publication 444-2 (IEC, 1980) is followed and measurements are made of the frequencies f_1 and f_2 corresponding to phase offsets of $\pm$ 45°, then C_1 can be calculated from

$$C_1 = (f_2 - f_1)/(2\pi R_{eff} f_S^2) \tag{8.3}$$

where the effective resistance R_{eff} is just the sum of the crystal resistance calculated in Eqn (8.1) and the pi-network terminating impedances, that is $R_{eff} = R + 25$.

The zero phase system can in principle measure unwanted modes with no more difficulty than encountered in measuring the principal crystal response, in contrast to CI meters, in which unwanted mode measurement is essentially beyond the capability of the system. The zero phase method has in addition the advantage that since the pi-network is matched to standard coaxial cables, it can be situated remote from the rest of the test system, making it relatively easy to configure environmental test systems. In particular, the pi-network can be located inside an oven to allow precise measurements of frequency–temperature characteristics.

8.4 AUTOMATED MEASUREMENT SYSTEMS

Although the absolute accuracy of the pi-network zero phase method may be questioned insofar as it depends critically on the reference resistors, the method nevertheless provides a workable standard within its operating frequency range. This is, however, limited to 125 MHz at best. Straightforward extensions to higher frequencies are complicated by the difficulty of constructing pi-networks and reference resistors that do not introduce unacceptable phase errors, and more fundamentally by the fact that at higher frequencies and overtones, zero phase frequencies may not exist. As shown in Section 6.3, when the figure of merit M of the crystal is less than the critical value 2, the crystal susceptance does not change sign, that is, there is no frequency interval where the crystal has an inductive impedance and there are no zero phase frequencies. Also, when M is only marginally greater than 2, the zero phase frequency differs appreciably from the resonance frequency of the motional arm of the crystal, which is usually of more significance.

There are several possible approaches to the problem of measurements at these higher frequencies:

(1) physical compensation of the crystal C_0, by one of several alternative means, to allow the continued use of the basic phase zero system;
(2) balanced bridge techniques;
(3) automatic network analyser techniques.

All of these have been proposed as candidates for a standard method of measurement at frequencies beyond the present limit of 125 MHz, but as yet no decision has been made as to which approach, if any, will be implemented. In terms of ease of use as a production tool as opposed to a standard, physical

C_0 compensation has considerable attraction in terms of speed and cost, but for standards purposes, the third option has the advantages of using readily available instruments, of allowing system calibration with traceable impedance standards, and of allowing the use of automated error correction procedures. It would therefore seem probable that at some time in the future a system of this general type will be selected as an international standard for crystal measurements.