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EIA STANDARD

STANDARD METHODS FOR MEASUREMENT
OF THE EQUIVALENT ELECTRICAL
PARAMETERS OF QUARTZ CRYSTAL UNITS, 1 kHz to 1 GHz

EIA-512

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Engineering Department

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STANDARD METHODS FOR MEASUREMENT OF THE EQUIVALENT ELECTRICAL
PARAMETERS OF QUARTZ CRYSTAL UNITS, 1 kHz to 1 GHz

(From EIA Standards Proposal No. 1792, formulated under the cognizance of
EIA P-5.4 Working Group on Quartz Crystals.)



STANDARD METHODS FOR MEASUREMENT OF THE EQUIVALENT ELECTRICAL PARAMETERS OF QUARTZ CRYSTAL UNITS, 1 kHz to 1 GHz

SCOPE:

Methods are described which permit determination of the values of the equivalent electrical parameters of piezoelectric quartz crystal units, utilizing automated measuring equipment. The methods described make use of standard coaxial terminations, standard calibrated mis-matched terminations, coaxial air-lines, and short-circuit terminations for both calibration of the instrument/test fixture error terms, and for verification of instrument performance. These coaxial standards, designed for 50 ohm systems, are readily available, and can be standardized in terms of national standards of impedance over very wide frequency ranges.

The measurement methods described are intended to provide standard reference values of the electrical equivalent parameters. Manufacturers and users may employ any other methods of measurement desired,^{10,12} however, when other methods are used, the values obtained shall be correlated to those obtained by the reference methods.

This standard is concerned only with the equivalent electrical network which approximates the admittance/impedance characteristic of a crystal unit over a relatively narrow range of frequencies near an isolated mode of vibration, at a particular excitation level. Non-linear amplitude behavior, or the presence of interfering modes of vibration, not only interfere with the actual measurement, but also render the accepted equivalent network representation invalid.

INTRODUCTION

The uses of piezoelectric crystal units in frequency control, filter and timing applications require accurate determination of the value of their equivalent electrical parameters. This document presents a reference method for measurement of the parameters of crystal units, based upon the use of automated state-of-the-art instrumentation systems which have become available in recent times. Using these methods, the measured parameter values are referenced to coaxial, traceable standards of impedance, and are essentially independent of the particular instruments used in the measurement.

Two basic methods are described: one, utilizing a two-port transmission method, characterizes the crystal unit as a three-terminal network; the second, utilizing a single-port reflection method, characterizes the crystal unit as a two-terminal device. Both methods yield the same values for the motional-arm parameter (R_1 , L_1 , and C_1), but the static capacitance parameters are different as discussed below.

Section I describes the equivalent electrical networks which characterize the crystal unit as a two-port and as a one-port device, and lists the parameters necessary to define the network behavior.

Section II presents a description of the two-port transmission measurement method recommended for characterizing the three-terminal equivalent network at frequencies below 100 kHz, where directional couplers are difficult to obtain.

Section III presents a description of a single-port reflectometer method for determining the two-terminal equivalent network parameters from 100 kHz to 1 GHz.

Section IV gives a description of the two-port s-parameter method for determining the two-port network parameters, recommended for frequencies from 100 kHz to 1 GHz.

Section V describes the calculations required to obtain the equivalent network parameters from the corrected values of transfer admittance obtained by any of the methods of Sections II, III, or IV.

All of the techniques of instrument calibration, data correction, and data reduction require extensive calculations, and are based on the utilization of a large number of individual measurements, which would not be feasible without the use of automated, software controlled instrumentation and computerized data reduction. However, it is the availability of these tools which permits the improved accuracy and reproducibility of results, and renders previously used manual measurement methods obsolete.

Section VI outlines measurement system considerations with respect to instrumentation and fixturing.

I. THE PIEZOELECTRIC CRYSTAL UNIT AND ITS ELECTRICALLY EQUIVALENT NETWORK

A crystal unit consists of a mechanically resonant piezoelectric vibrator (usually a plate, bar, or tuning fork) with electrodes attached to or supported near to the element to excite one of its resonant frequencies. The electrical behavior of the crystal unit, as evidenced by the electrical admittance (or impedance) observed from its terminals, over a narrow range of frequencies near a resonance, can be represented by an equivalent electrical network. When the resonant mode of interest is sufficiently isolated from other modes of motion, the parameters of the equivalent network may be considered to be independent of frequency, and the equivalency will be nearly exact over a frequency band of at least a few percent. (If the mode of interest is not essentially isolated, the methods of measurement presented may still be used to determine the impedances of the unit, but any attempts to relate the frequency dependence of its impedance to the electrically equivalent network of Figure 1 will be futile!)

Figure 1A shows the three-terminal equivalent-circuit representation of a crystal unit which is valid over a few percent band centered at resonance for an isolated mode of vibration. There are six parameters shown:

- C_{13} = Static capacitance from pin 1 to enclosure
 C_{23} = Static capacitance from pin 2 to enclosure
 C_o = Static capacitance from pin 1 to pin 2,
 including the capacitance between electrodes
 and between support structures
 R_1 = Series resonant resistance
 L_1 = Motional inductance
 C_1 = Motional capacitance

If the crystal unit is considered to be a two-terminal element (enclosure connection neglected), it has an electrical equivalent as shown in Figure 1B. The motional parameters (R_1 , L_1 , and C_1) are the same as above; however, the value of C_o will include the series combination of C_{13} and C_{23} , as well as some effects of the capacitance from enclosure to ground. The frequency dependence of device impedance will only be modeled as well as the various components of the composite C_o are known. Consequently, the two-terminal equivalent circuit is recommended for use only in those applications where operation at a single frequency near series resonance is anticipated.

The static capacitance values are quite easily measured by conventional means, as they are relatively independent of frequency and not related to the resonant properties of the vibrator. C_o will be slightly influenced by the impedance of the measuring circuit, as the free and clamped values for piezoelectric materials are different, depending on the piezoelectric coupling coefficient;¹ for quartz crystals, however, the effect is small, and a quite satisfactory value of C_o can be obtained, for example, as the average of a value measured a few percent below resonance, and a second value measured a few percent above anti-resonance.

The trans-admittance (admittance between pins 1 and 2) of the crystal unit is quite accurately modeled by that of the equivalent network in Figure 1A, over a band of frequencies extending several percent above and below resonance. Fortunately, this bandwidth is adequate to describe the behavior of almost any circuit in which the device will be used. The admittance characteristic is shown in Figure 2A, which is the admittance-plane locus of the vector relationship

$$\overline{Y}_{12} = \frac{R_1}{R_1^2 + (\omega L_1 - \frac{1}{\omega C_1})^2} + j \left[\omega C_o - \frac{(\omega L_1 - \frac{1}{\omega C_1})}{R_1^2 + (\omega L_1 - \frac{1}{\omega C_1})^2} \right] \dots [1]$$

This circular locus in the Y-plane clearly maps into a corresponding circular locus in the Z-plane, as shown in Figure 2B. There are several characteristic values which are commonly used in describing crystal units, whose relationship becomes clear from examination of Figure 2. The "fundamental" constants which depend only on the motional properties of the vibrator are the series resonant frequency, f_s , and the values of R_1 , L_1 , and C_1 , associated with the motional arm circuit. The other frequencies of interest are:

- f_m = frequency of minimum impedance
- f_r = frequency of zero-phase, low impedance
- f_a = frequency of zero-phase, high impedance
- f_n = frequency of maximum impedance
- f_p = parallel resonance frequency (lossless)

Clearly, all of these frequencies depend to at least some degree upon the effective value of C_o ; since connection into any use-circuit will almost inevitably produce some additional stray capacitance at the terminals and therefore modify the effective C_o value, best correlation of measurements will be obtained if the series resonant frequency, f_s , is referenced.

A list of symbols used for the equivalent electrical network is given in Table 1. The values of effective resistance at each of the characteristic frequencies can be determined from the real components of the impedance and admittance vectors, as shown in Figure 2. The motional inductance (or capacitance), however, can only be determined from a knowledge of the frequency-dependence of the imaginary component. Figure 3 is a graphical presentation of the magnitudes of the real and imaginary components of device impedance versus frequency, with the characteristic frequencies marked. It can be shown² that the value of motional inductance is very accurately determined from the derivative of reactance with respect to frequency, evaluated at f_s , after the admittance circle has been translated to have its center lie on the real axis in the Y-plane. This translation is accomplished mathematically by subtracting an amount $\omega_s C_o = B_o$ from the susceptance component of each measured admittance vector. Then, the remaining admittance vectors, representing only the components due to the motional arm parameters, are transformed to impedance vectors;

$$Z = R + jX = \frac{1}{Y} = \frac{1}{G + jB}$$

and the reactance component, X , may be fitted to a function of frequency. f_s , the series resonant frequency, is the value of f at which the fitted function is zero. Then, differentiation of the fitted function gives

$$L_1 = \frac{1}{4\pi} \left. \frac{\partial X_e}{\partial f} \right|_{f=f_s}$$

and C_1 can then be determined from

$$C_1 = \frac{1}{4\pi^2 f_s^2 L_1}$$

Table 2 gives the relationship of the other characteristic frequencies to the value of series resonance frequency, f_s , in terms of the ratio of capacitance, $r = \frac{C_o}{C_1}$, and

figure of merit, $M = \frac{Q}{r}$, of the resonator. These approximations are quite accurate for values of $r > 25$, and $M > 10$, when considering fundamental-mode resonators. For high-overtone crystal units with large r -values and low- Q , however,

f_m and f_r are no longer symmetrically located about f_s .

A word of caution is in order at this point: the above relationships hold exactly for the equivalent circuit with constant parameter values, but do not necessarily hold for real crystal units, whose characteristics will be sensitive to both temperature and drive level, even when the resonance being measured is adequately removed from any other mode of vibration. The parameter values obtained from a measurement of a real crystal unit will depend upon the conditions at the time of measurement.

II. TWO-PORT CRYSTAL UNIT MEASUREMENTS AT LOWER FREQUENCIES

At lower frequencies (i.e., below about 100 kHz), the shunt capacitances C_{13} and C_{23} can usually be neglected, as they appear in shunt with the 50Ω system impedances and will have an extremely small effect on the measured parameters. For example, figure 4 shows the test circuit connection for transmission measurement of low-frequency crystal units.

In order to obtain the transimpedance function of the crystal unit, it is necessary to determine the voltage transfer function at several frequencies near resonance. Errors which may occur during measurement include variations of source voltage, and non-linearities in the detector, as well as errors in the actual source and detector impedance. For practical purposes, the source and detector impedances may be considered accurate at low frequencies, or may be verified in terms of known standard resistances inserted in place of the crystal unit.

To minimize errors due to source variations, measurements are made in terms of the ratio of the transmission voltage (e_a) to the reference voltage (e_r). Non-linearities of the detector are calibrated by means of known, matched attenuators. Since both amplitude and phase of the voltage-ratios are measured, any systematic phase errors due to the power-splitter, test fixture, and line-lengths, are included in the calibration factors. To minimize the possibility of faulty data, each measurement should be repeated several times, the values examined for "sports", and the average of the "good" readings saved as the measured value.

Calibration (or normalization) of the instrument consists of setting the frequency and level of the excitation source to that desired, and connecting test-ports 1 and 2 with a short thru-line. The voltage-ratio e_a/e_r is then determined:

$$e_{a,p} = e_a/e_r$$

Since the source and detector impedances are known to be equal, the "effective" source-to-reference ratio at this excitation level is determined:

$$e_s^1 = \frac{e_s}{e_r} = 2 \times e_{a,p} \quad (1)$$

The detector linearity of the measurement system may be verified and any necessary corrections determined, by means of standard matched attenuators of known value. (Attenuators with calibration traceable to NBS are readily

available.) Because the error terms are expected to be small, use of three or four standards should give adequate representation of the errors. Values of 10dB, 20dB, 40dB, and 60dB will cover the expected range of loss during measurement of crystal units. One may express the linearity errors as

$$e_{\text{true}} = e_{\text{meas}} + \Delta e_{\text{err}}$$

and the error may be expressed as a function of the measurement:

$$\Delta e_{\text{err}} = a + be_{\text{meas}} + ce_{\text{meas}}^2 \quad (2)$$

Knowing the effective source-to-reference ratio e_s^1 , and the actual value of each standard attenuator, the true transmission level with an attenuator of α_{dB} is therefore

$$e_{\text{true}} = \frac{1}{2} e_s^1 \times 10^{\frac{\alpha}{20}}$$

With this attenuator connected, let e_m represent the measured value of e_a/e_r ; then, the instrument magnitude errors at this voltage level is

$$\Delta e_{\text{err}} = e_{\text{true}} - e_m = \frac{1}{2} e_s^1 \times 10^{\frac{d}{20}} - e_m$$

With four or more paired values of $\langle \Delta e_{\text{err}}, e_m \rangle$, the coefficients of the error function

$$\Delta e_{\text{err}}(e_m) = a + be_m + ce_m^2 \quad (3)$$

may be determined by a least-squares method, and stored. For any measured voltage-ratio, then, the corresponding value of correction may be calculated and applied to obtain the "true" voltage-ratio value which represents the transmission ratio. Generally e_s^1 , and the coefficients of the e_{err} function, will all have at least some dependence on frequency as well as source voltage level. A recommended procedure to "calibrate" the system over a reasonable frequency range is the following:

- a. Set the source level to that desired
- b. With a thru-line connected in place of the device-under-test, determine the effective source-to-reference vector (e_s^1 , Eqn. 1) at several frequencies within the range of interest.
- c. The real and imaginary components of e_s^1 may each be fitted to a polynomial function of frequency (a quadratic function is usually adequate for a frequency band of 10% to 20%). The coefficients of these functions are then saved, and used to obtain the desired value of e_s^1 at any frequency within the band.
- d. Also, at each of several frequencies within the band, the non-linearity error term is evaluated, as described above. Then, each set of the coefficients (a, b, and c) is fitted to a polynomial function of frequency: