LOAD RESONANT MEASUREMENTS OF QUARTZ CRYSTALS

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ABSTRACT

The measurement of load resonant frequency can be accomplished using several measurement techniques. Load resonant frequency measurements with Transmission Systems and Crystal Impedance Meters are examined along with the measurement difficulties of each method. Potential sources of correlation differences are discussed including the impact of the crystal spurious responses on the load resonant measurement.

INTRODUCTION

A quartz crystal is used at either the series resonant frequency, determined by the motional parameters of the crystal, or at a load resonant frequency that is determined by the crystal's motional parameters and the value of an external load reactance. Normally this external reactance is a capacitor, with the resulting load frequency slightly higher than the series resonant frequency.

Load resonant frequency measurements are inherently difficult to make because of the accuracy and repeatability required for the measurement and because the crystal itself impacts the resolution of measurement. In addition, the associated strays of the measurement circuit can have a pronounced impact upon the measurement being made. These difficulties are examined for load resonant frequency measurements made on Transmission Systems and Crystal Impedance Meters. The measurement techniques presented are those typically used in the industry. The techniques described for the Transmission System are also applicable to an S Parameter Measurement System.

EQUIVALENT CRYSTAL CIRCUIT

The basic electrical equivalent circuit for a quartz crystal operated at load resonance is shown in Figure 1.

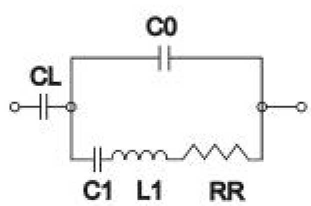


Figure 1

Where: CL = Load Capacitor (pF)
C1 = Motional Capacitance (pF)
L1 = Motional Inductance (mH)
RR = Crystal Resistance (ohms)
C0= Static Capacitance (pF)

The load resonant frequency can be shown to be[1] :

$$FL = FR\left[\frac{C1}{2(C0+CL)}+1\right] \qquad \text{[Equation 1]}$$

Where: FL = Load Resonant Frequency (Hz)
FR = Series Resonant Frequency (Hz)

When a crystal is measured with a physical load capacitor there are additional stray terms that are introduced into the circuit. The most prominent terms are the stray capacitance present at the junction of the crystal and the external load capacitor, the stray capacitance across the crystal, and the lead inductance of the circuit. Figure 2 shows the electrical model including these terms.

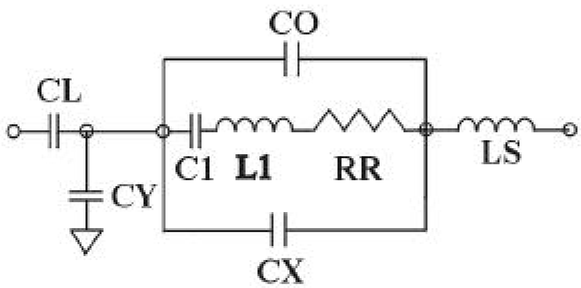


Figure 2

Where: CY = Stray Capacitance (pF)
CX = Stray Capacitance (pF)
LS = Lead Inductance (nH)

The load resonant frequency of this circuit including the circuit stray reactance is shown in Equation (2).

$$FL = FR\left[\frac{C1(CL+CY-CLS)}{2((CL+CY)(C0+CX)-CLS(C0+CL+CX+CY))}+1\right]$$ [Equation 2]

Where: $$CLS = \frac{10^{21}}{4\pi^2 FR^2 LS}$$

The measurement of load resonant frequency and the impact of these strays for both Transmission Systems and Crystal Impedance Meters are discussed in the following paragraphs.

TRANSMISSION MEASUREMENT SYSTEMS

The IEC-444 [2] Standard defines a method of measuring the series resonant frequency and motional parameters of a quartz crystal using a frequency synthesizer and a vector voltmeter. A block diagram of this system is shown in Figure 3.

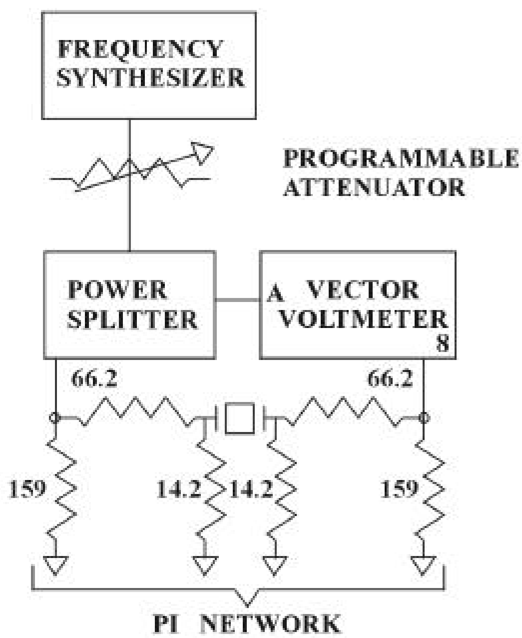


Figure 3

The Transmission System first measures the static capacitance of the crystal at a frequency that is far removed from the resonant frequency of the crystal. The frequency synthesizer is then stepped in the vicinity of resonance and impedance measurements are made. The reactance of the static capacitance is subtracted from these measurements which results in the motional arm reactance and resistance. The measurement iteration continues until the motional arm reactance equals zero. Series resonant frequency and resistance are then determined at this point. The motional capacitance is derived from the slope of the motional arm reactance as indicated by Equation (3).

$$C1 = \frac{10^{12}}{\pi \, XS \, FR^2} \qquad \text{[Equation 3]}$$

Where: XS = Reactance slope (Ohms / Hz)

Load resonant frequency can be determined with a Transmission System using three distinct methods of measurements: "Calculated" "Measured", and "Physical Capacitor".

Method # 1 - "Calculated" Load Frequency

In this method of load resonant frequency measurement, the load frequency is directly calculated using Equation (1). The standard measurement configuration shown in Figure 3 is used to make the static capacitance, series resonant frequency, and motional capacitance measurements required to calculate the load resonant frequency. The series resonant frequency and motional parameters are determined from measurements made in the vicinity of series resonance.

The circuit stray reactances indicated in Figure 2 have minimal impact upon the measurement. The CY stray term is shunted out by the 14.2 ohm terminating resistor of the PI Network. The CX and LS terms are determined during system calibration and are mathematical removed from the crystal measurements.

The resolution of the "Calculated" load frequency measurement depends upon the crystal being measured. Typical resolutions are from 0.5 ppm to 3 ppm. Figure 4shows the distribution printout of 500 measurements of a single crystal measured on an S&A 350A System. The frequency spread for this example was 2.3 ppm with a standard deviation of 0.45 ppm.

The "Calculated" technique is the simplest method of accomplishing load resonant frequency measurements with a Transmission System. The repeatability and accuracy of the series resonant frequency and motional parameters are not affected by this measurement method.

Typical series resonant frequency resolution for an S&A 350A System is 0.1 ppm to 0.2 ppm.

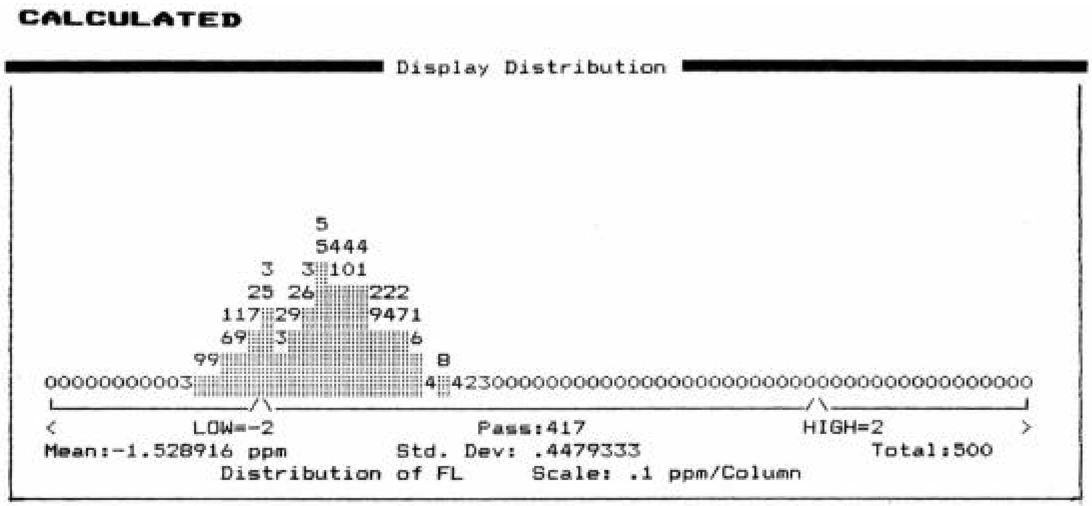


Figure 4

Another advantage of the "Calculated" method is that no additional measurements are required to determine load resonant frequency. The total measurement time required for the crystal measurement is not affected by this method.

The "Calculated" method of measurement can result in an error at load frequency if the crystal does not follow the frequency relationship indicated by Equation (1). The accuracy of the load frequency measurement is also affected by the resolution and accuracy of the static and motional capacitance measurements.

The "Calculated" method of measurement can be used on those crystals that are known to follow the relationship indicated by Equation (1) and do not require the measurement resolution offered by other measurement techniques.

Method #2 - "Measured" Load Frequency

This measurement method first measures the series resonant frequency and motional parameters in the same manner as in the "Calculated" method. Using that information the system then calculates the load frequency, sets the synthesizer to that frequency, and makes an impedance measurement. The displayed load frequency is then adjusted linearly based upon the difference between the calculated impedance and the measured impedance.

The "Measured" load frequency technique uses the standard PI Network of Figure 3. The impact of the stray terms shown in Figure 2 is the same as described for the "Calculated" method: The CY stray capacitance is shunted by the 14.2 ohm PI Network terminating resistor and the CX and LS terms are removed mathematically.

The resolution of the load frequency measurement is a function of the impedance measured at the calculated load frequency. As the impedance becomes large (greater than 1000 ohms) the measurement resolution decreases.

Equation (4) shows an approximate relationship of impedance magnitude and load capacitance.

$$Z = \frac{1}{2\pi \, FL \, CL} \qquad \text{[Equation 4]}$$

Where: Z = Impedance magnitude (Ohms)

Figure 5 shows the distribution of 500 repeated measurements of the same crystal used for the measurements of Figure 4 . The frequency spread for this crystal was 0.6 ppm with a standard deviation of 0.1 ppm. The magnitude of the impedance of this measurement was approximately 625 ohms.

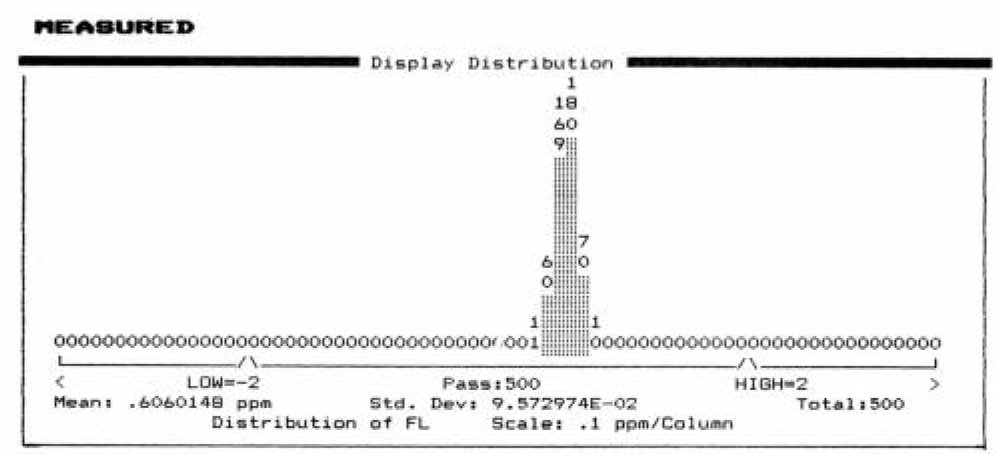


Figure 5

A significant advantage of the "Measure" method is that nonlinear crystal responses that would invalidate the frequency relationship defined by Equation (1) are included in the measurement.

This measurement method requires an additional measurement at the load resonant frequency. For an S&A 350A system this extends the total measurement time per crystal from a typical 1.2 seconds to 1.4 seconds.

The magnitude of the impedance defined in Equation (4) limits the maximum current that the system can provide to the crystal. The crystal is a current sensitive device and should be tested in the vicinity of the specified operating power. Typically magnitudes of impedance less than 1000 ohms can be measured using this technique.

Method # 3 - "Physical Capacitor"

An alternate method of measuring load frequency is to place a physical capacitor in series with the crystal. The crystal and load capacitor combination present the measurement system with a "new" crystal with a different resonant frequency and different motional parameters. This "new" crystal is measured in the same manner as described for the "Calculated" method. The frequency measured is the load frequency of the crystal at that value of load capacitance. The motional parameters measured correspond to the "new" crystal and must be mathematically corrected to obtain the correct parameters of the crystal.

When a physical capacitor is added to the PI Network, the junction between the crystal and the load capacitor becomes a point of high impedance. The stray capacitance at this junction, indicated in Figure 2 as CY, now has a significant impact upon the measurements. The total load capacitance in the circuit now includes the load capacitor, the stray to ground (CY), and the pin to pin capacitance (CX). The impact of these stray terms is shown by the following equations.

$$C0 = \frac{(C0m+CX)(CL+CY)}{CL\text{-}C0m\text{-}CX} - CX \qquad \text{[Equation 5]}$$

$$C1 = \frac{C1m(C0+CX+CY+CL)^2}{CL(CL+CY)} \qquad \text{[Equation 6]}$$

$$RR = \frac{Rm\ CL(CL+CY)}{(C0+CX+CL+CY)^2} - \frac{10^9}{2\pi\, FL\ CL} \qquad \text{[Equation 7]}$$

Where: COm = Measured C0 (pF)
C1m = Measured C1 (pF)
Rm = Measured RR (Ohms)

These equations assume that the crystal cover is not grounded. If the cover is grounded, an unknown capacitance from the crystal electrode to the cover is in parallel with the CY stray term. Since this capacitance is indeterminate, the equations above are not applicable.

The CY term depends upon the physical layout of the test socket and is included as a constant in the measurement software. The CX and LS stray terms are determined during system calibration.

The "Physical Capacitor" technique results in very repeatable load frequency measurements. Typical resolution of load frequency measurements is from 0.1 ppm to 0.2 ppm. Figure 6 below shows the same crystal of Figure 4 measured 500 times using the "Physical Capacitor" method. The frequency spread indicated is 0.2 ppm with a standard deviation of 0.03 ppm.

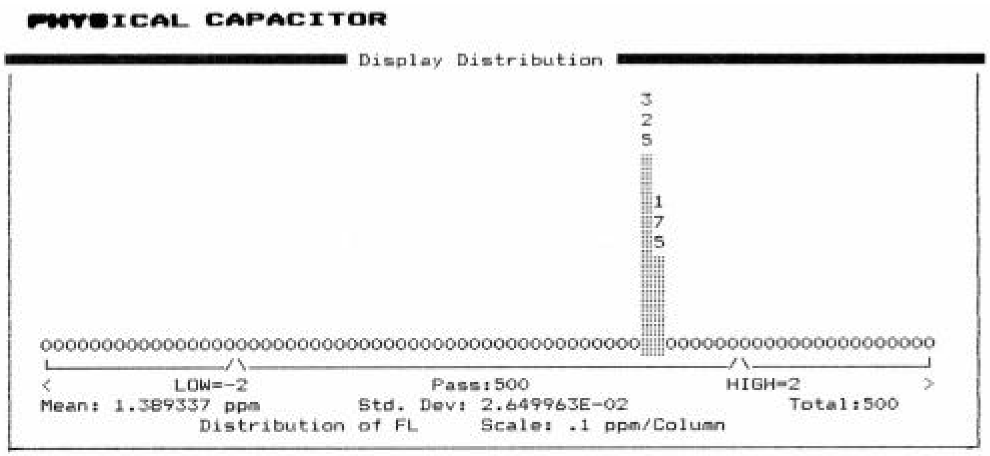


Figure 6

The "Physical Capacitor" method typically can provide the specified drive current into the crystal. The crystal is in resonance with the physical capacitor and the resulting combination presents a low impedance to the PI Network. Non-linear crystal responses at the load resonant frequency are also directly reflected in the measurement.

The measured parameters are not as accurate with this method as those measured without a physical capacitor because of the required mathematical transformations. In addition any variation in the stray CY term will result in a measurement error. The "Physical Capacitor" also requires the standard PI Network to be modified to accept a load capacitor in series with the crystal.

The series resonant frequency and motional parameters could be measured with the same repeatability of the "Calculated" method by replacing the load capacitor with a short. This can effectively be done in a 350A System by installing an additional series resonant frequency test port. The disadvantage of this technique is that the frequency measurements are made twice: once at load resonance and once at series resonance. The typical measurement time of an S&A 350A system using the "Physical Capacitor" method and an additional series resonant measurement port is extended from 1.2 seconds to 2.0 seconds.

The "Physical Capacitor" method should be used when the greatest repeatability of load resonance measurements is required. This method is also appropriate for those crystals that require a higher drive current than the "Measured" method can provide.

Each of the measurement methods of load resonant frequency for a Transmission System has unique advantages and disadvantages. The best method for a particular crystal depends upon the specific testing requirements.

Temperature Testing at Load Resonant Frequency

The impact of temperature on a crystals's frequency and resistance can be examined using the measurement techniques and equipment described previously along with a precision temperature test chamber. An S&A 2200 Temperature Test System using the S&A 350A

Transmission System and an S&A 4220MR Temperature Chamber was used to measure an example crystal. A crystal was selected that does not follow the frequency relationship of Equation (1). The measurements made on this crystal illustrate the differences between the Transmission System methods of measurement. This crystal was specially selected for this example and represents a possible measurement condition but not a typical one.

A total of four measurement runs were made. The first run was at series resonant frequency, the remaining three runs were performed at load resonant frequency using the "Calculated", "Measured", and "Physical Capacitor" methods of measurement. The crystal was measured over a temperature range of 0 degrees C to 60 degrees C.

Figure 7 is the output from the measurement run made at series resonant frequency. The graph shows frequency and resistance information as a function of temperature. The frequency data is first curve fit to a third (or fourth) order polynomial function. This curve is then plotted along with the deviation of the measured frequency from the calculated curve. It is presented in this manner so that any nonlinear characteristics in the crystal's response can be easily seen.

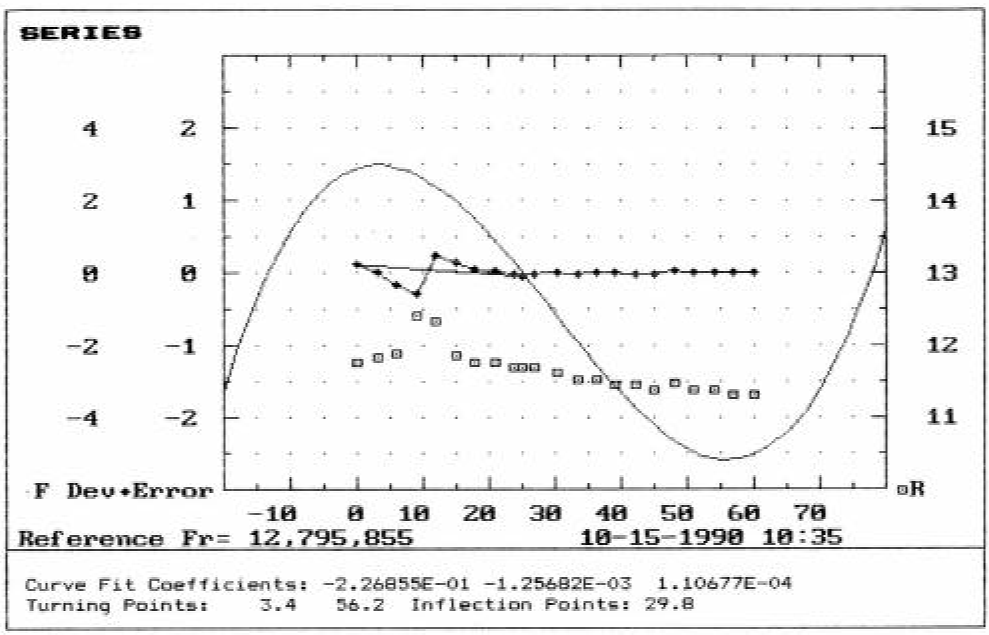


Figure 7

A nonlinear response or perturbation in frequency and resistance at 10 degrees C is evident in Figure 7. This perturbation is due to a coupled mode of vibration which invalidates the frequency relationship of Equation (1) .

Figure 8 shows measurements of the same crystal at a load capacitance of 18 pF using the "Calculated" method of measurement.

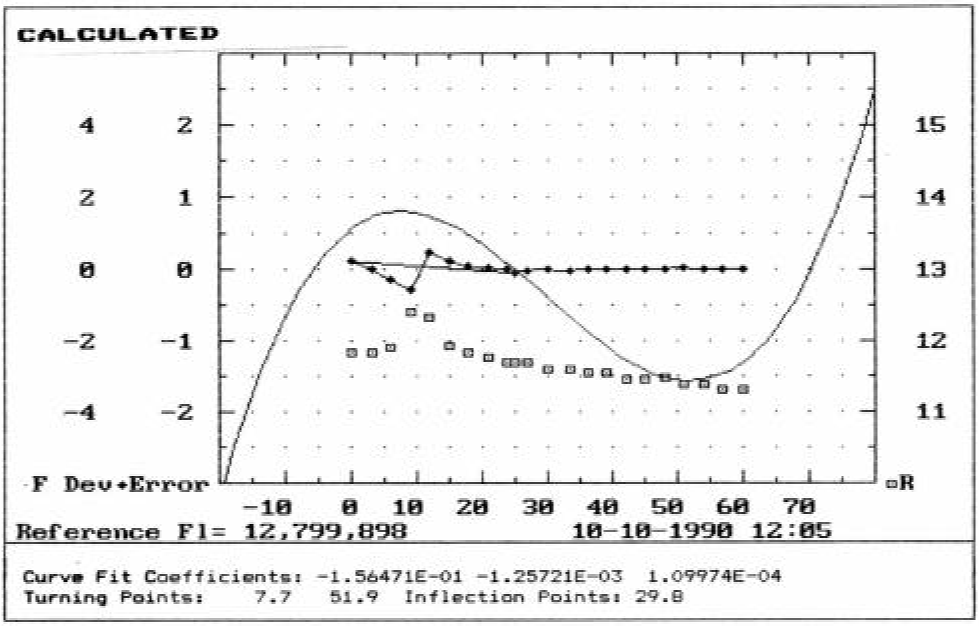


Figure 8

The coupled mode is still present in the data because the measurements made using the "Calculated" method are at series resonance. This coupled mode, however, does not exist at the load resonant frequency specified. The "Calculated" method results in the perturbation at series resonance being displayed inappropriately at the load resonant frequency.

The plot of the crystal using the "Measured" method of measurement is shown in Figure 9.

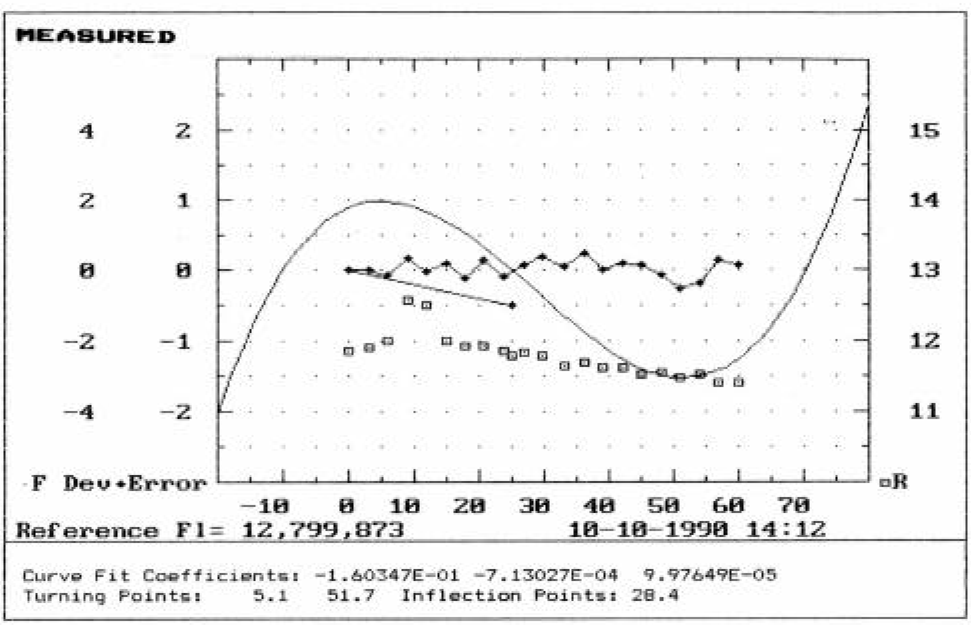


Figure 9

The coupled mode is no longer present in the frequency information because the frequency was measured at the load resonant frequency of the crystal. The motional parameters are still measured at series resonant frequency as indicated by the presence of the resistance perturbation.

Figure 10 shows the measurements made using the "Physical Capacitor" method of measurement.

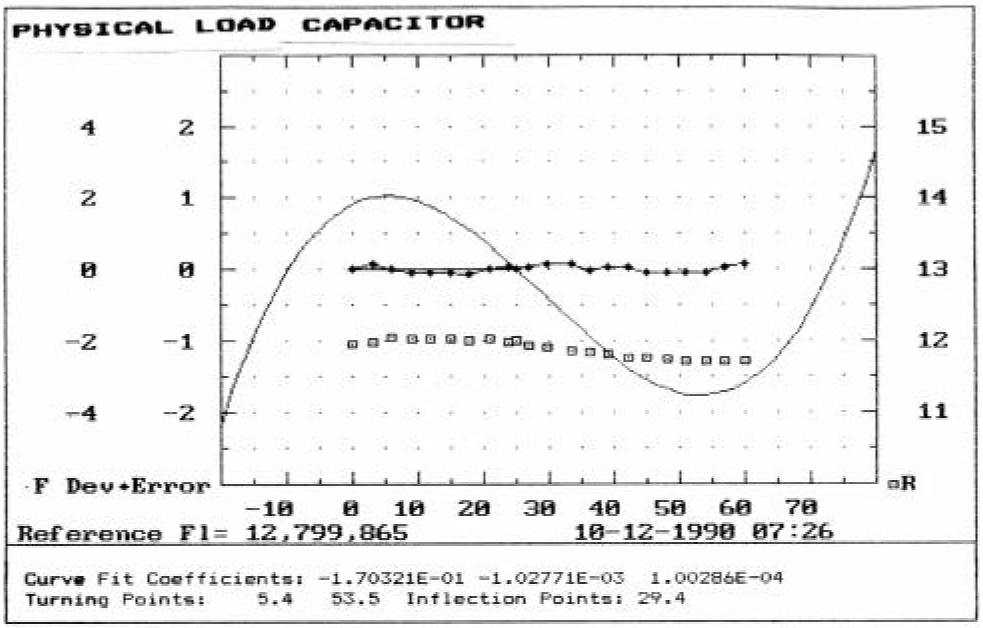


Figure 10

Since the frequency and motional parameter measurements are made at load resonant frequency, the coupled mode at series resonant frequency has no effect on the displayed data.

As these figures indicate, the presence of a nonlinear crystal response at the load resonant frequency can be detected using the "Measured" or "Physical Capacitor" method of measurement. These two methods actually measure the crystal at the specified load resonant frequency.

In comparing Figures 7, 8, 9, and 10 a difference in the first order coefficient of the curve fit between the series resonant measurements and the load resonant measurements is evident. This difference is due to the temperature coefficient of the piezoelectric coupling factor. We have observed that this is essentially linear and can be expressed as indicated in Equation (8).

$$K = \left(A0(L) - A0(S)\right)\left[\frac{FR}{FL\text{-}FR}\right]$$ [Equation 8]

Where: K = Piezoelectric Coupling Temperature Coefficient
A0(L) = First Order Curve Fit Coefficient at Load Resonant Frequency
A0(S) = First Order Curve Fit Coefficient at Series Resonant Frequency

The "Calculated" method shown in Figure 8 reflects a fixed piezoelectric coupling temperature coefficient used by the S&A 2200 system of 220 ppm/deg.C.

The "Measured" method of measurement (Figure 9) resulted in a temperature coefficient of 212 ppm/deg.C. This value is technically the most correct for this crystal because the stray capacitances of the test circuit do not impact the measurements.

The "Physical Capacitor" measurements shown in Figure 10 indicate a temperature coefficient of 180 ppm/deg.C. This value is affected by the temperature coefficient of the physical capacitor and any changes in the test circuit strays as a function of temperature.

These small differences in the temperature coefficient of the piezoelectric coupling factor are reflected in the graphs of the third order frequency curvefit. The worst case measurement error due to these differences is 1 ppm at 55 deg. C.

A coupled mode as indicated in Figure 7 has a negative coefficient that is typically in the range of -5 ppm/deg.C to -25 ppm/deg.C. As shown in the previous paragraphs, the presence of a coupled mode can be missed or incorrectly indicated if the test is not performed at the specified load resonant frequency. The "Measured" and "Physical Capacitor" measurement methods provide the capability of detecting these coupled modes.

The "Physical Capacitor" method can be used even if the physical capacitor is not precisely the same value as the specified load capacitor. In this case the temperature test range can be extended so that any coupled modes would be apparent. For example, a crystal that is tested at a frequency 50 ppm lower than the specified load frequency should be tested at a maximum temperature of at least 10 deg.C (-50/-5) greater than that specified. A crystal that is tested at a frequency 50 ppm more than the specified load frequency should be tested at a minimum temperature that is 10 deg.C less than that specified [4].

CRYSTAL IMPEDANCE METERS

A Crystal Impedance (CI) Meter is specifically designed for measuring the electrical parameters of a quartz crystal. These instruments contain a tuned oscillator circuit.

frequency counter, and a capacitance meter. A block diagram of a CI Meter is shown in Figure 11.

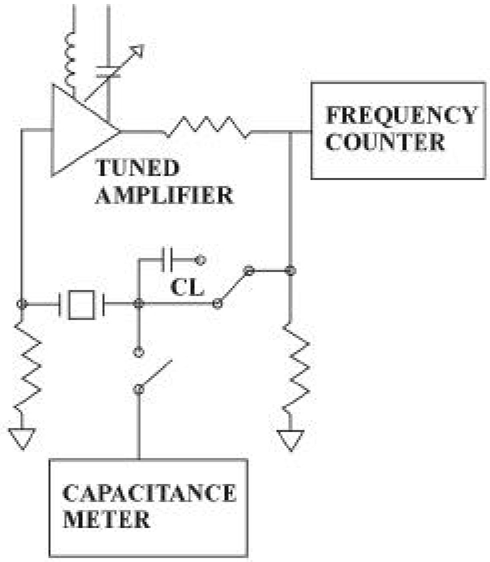


Figure 11

In order to measure a crystal, the tuned circuit is setup near the frequency of interest. The crystal is then inserted into the test socket. The CI Meter first measures the static capacitance, resistance, and series resonant frequency of the crystal. A known load capacitance is then switched in the circuit and a load resonant frequency is measured. The motional capacitance is then calculated using Equation (1). If the specified load capacitance is different than the known capacitance, the load resonant frequency is calculated using the measured motional capacitance and Equation (1).

The effects of the stray lead inductance (LS), shown in Figure 2, is minimized by tuning the oscillator's tank circuit with a resistor of approximately the same resistance as the crystal. This results in approximately zero phase shift across the test socket. If the value of the stray lead inductance is known, the frequency measurements can also be mathematically corrected using Equation (2). The stray capacitance terms (CY, CX) are included in the measurement of the known load capacitor.

A crystal was measured 500 times using an S&A 150D CI Meter. Figure 12 shows the distribution of these measurements. From this information the frequency spread for this example was 0.6 ppm with a standard deviation of 0.1 ppm.

A typical Crystal Impedance Meter has an upperfrequency limit of 60 Mhz. This limit is usually inconsequential for load resonant measurements, but can be a significant performance limit for high frequency overtone crystals used at series resonance.

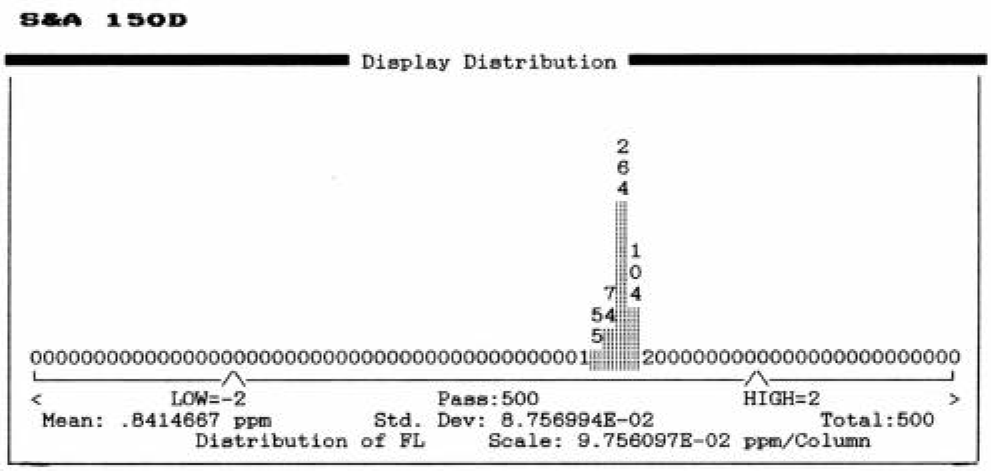


Figure 12

The significant advantage of Crystal ImpedanceMeters is their cost. Several Crystal Impedance Meters can be purchased for the price of a single Transmission System.

Temperature Testing at Load Resonant Frequency

An S&A 2150 Temperature Test System was used to measure the frequency and resistance deviation of an example crystal. The S&A 2150 system uses an S&A 150D Crystal Impedance Meter and an S&A 4220MR temperature test chamber. Figure 13 shows the measurements of the example crystal over a temperature range of 0 deg.C to 60 deg.C.

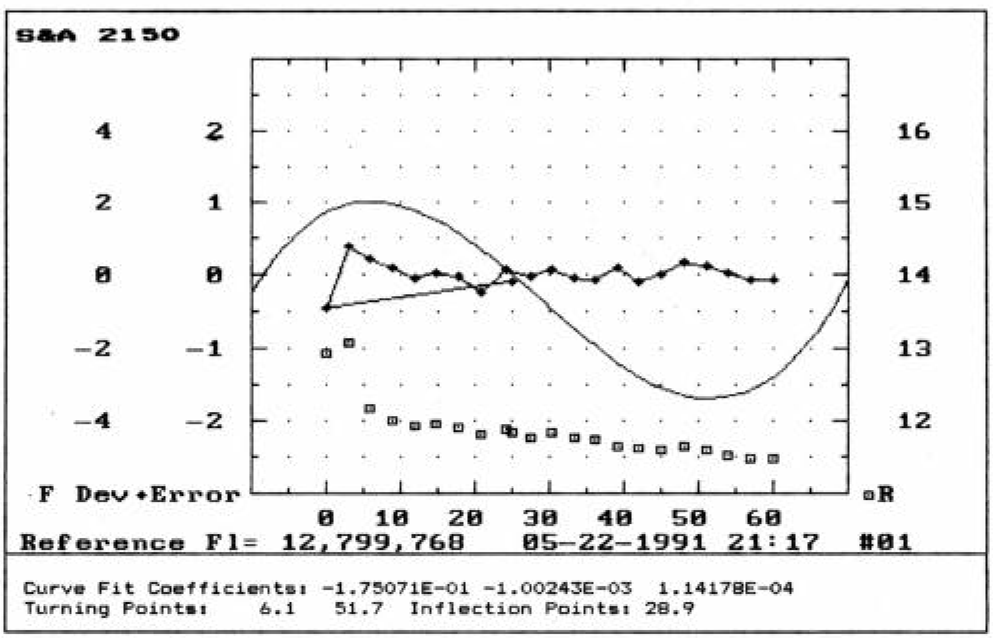


Figure 13

The S&A 2150 uses a fixed piezoelectric coupling factor temperature coefficient of 220 ppm/deg.C. This is the same correction as described for the "Calculated" Transmission System measurement method.

The S&A 2150 system measures the motional parameters of the crystal at the first temperature point. Subsequent measurements are made at series resonance and then converted to load resonance frequency using Equation (1). This technique can result in an error in the displayed data if a coupled mode is present. A coupled mode is not common in a crystal but should be considered if there are significant correlation errors between the S&A 2150 System and other methods of measurement.

LOAD RESONANT FREQUENCY MEASUREMENT CORRELATION

The ability of a measurement system to determine the load resonant frequency is a function of the crystal and the specified load capacitance. For example, a 12 MHz crystal with a frequency specification of +/- 10 ppm is more difficult to measure at a load capacitance of 18 pF than at 30 pF. A better method of specification is to specify the frequency as absolute and allow a tolerance on the load capacitance. The specification for the 12 MHz part could be given as 12 MHz at 18 pF +/- 0.5 pF. The specification on load capacitance can be converted to a frequency tolerance by multiplying by the trim sensitivity of the crystal at that value of load capacitance. The trim sensitivity is defined as derivative of the load frequency with respect to load capacitance. Equation (9) can be used to calculate this value from the other crystal parameters.

$$TS = \frac{500000\,C1}{(C0+CL)^2} \qquad \text{[Equation 9]}$$

Where: TS = Trim Sensitivity (ppm/pF)

For the 12 MHz crystal example, the trim sensitivity was 20 ppm/pF. This means the +/- 0.5 pF specification on the load capacitance would be mathematically equivalent to tolerance of +/- 10 ppm on the load frequency. However, it is easier to explain to a crystal user how small 0.5 pF is, than to explain a frequency variation of 10 ppm.

Ten crystals of various load resonant frequencies were measured using two different Crystal Impedance Meters and the three methods of Transmission System measurement. The temperature of the crystals was controlled during these measurements at 25.0 deg.C with an S&A 4220MR temperature chamber.

The first CI Meter used to make these measurements was an S&A 150C. The S&A 150C requires a setup resistor for each crystal. A variable load capacitor must also be adjusted to the value required for the crystal to be tested. The load resonant frequency is determined by switching in the load capacitor and reading the resulting frequency.

The second CI Meter used for these measurements was an S&A 150D. This CI Meter uses a fixed internal resistor to setup the tuned circuit. The frequency measurements are mathematically corrected for the stray lead inductance (LS) as indicated by Equation (2). The load resonant measurement uses a fixed load capacitor of28 pF. The load frequency at a different load capacitance is calculated using Equation (1).

An S&A 350A Transmission System was used to measure these crystals with the "Calculated", "Measured", and "Physical Capacitor" methods of measurement.

The crystals measured were all fundamental mode crystals. The load capacitor specification varied from 32 pF for the 1 MHz crystal to 15 pF for the 30 MHz crystal. The measurements for these crystals are listed in Table 1.

	CL	TS	150D	150C	350A-C	350A-M	350A-P
1	32	3.3	999907	1.0	1.0	3.0	-1.0
2	30	3.0	4193759	2.1	0.7	0.0	-1.0
3	30	4.5	5002841	3.6	-0.2	-0.6	-1.0
4	22	13.3	10000039	2.4	2.7	-4.6	-3.1
5	20	12.1	12799385	2.4	0.0	-0.2	-1.6
6	20	19.4	15257437	1.5	5.0	0.7	-4.1
7	15	27.2	18296994	2.1	7.8	0.8	-6.7
8	15	22.5	20009678	0.7	2.8	1.3	-2.8
9	15	26.6	21346530	2.1	4.6	-2.6	-5.3
10	15	24.8	30137215	-0.5	7.7	-4.1	4.2

Table 1

The worst case difference was 7.8 ppm for crystal #7 using the "Calculated" method of measurement. This crystal has a trim sensitivity of 27.2 ppm/pF. The 7.8 ppm difference corresponds to a load capacitance error of only 0.3 pF.

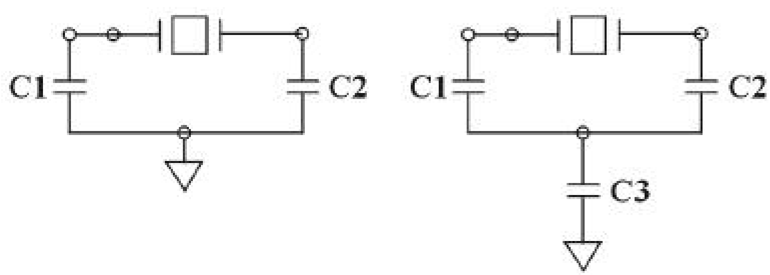
The correlation of measurements between instruments is impacted by many factors. The following paragraphs discuss some of these factors and how they affect the measurement methods previously described.

Crystal Drive Level

It is important to remember that the crystal is a current sensitive device. Crystal measurements should be performed at the specified operating power level. We recommend that a crystal be tested at a drive level of 500 microwatts or less. Higher power levels can cause the crystal to become nonlinear [5]. This nonlinearity results in errors in the frequency measurement of the crystal. The current trend in the industry is to specify even lower power levels than 500 microwatts as older specifications are rewritten to reflect current crystal products.

Crystal Cover Connection

The manner in which the crystal cover is connected will impact the load resonant measurement [3]. The crystal is actually a three terminal device as shown in Figure 14.



Cover Grounded — Cover Ungrounded

Figure 14

Where: C1, C2 = Capacitance between Crystal Electrodes and Ground (pF)
C3 = Capacitance from Crystal Cover to Ground (pF)

The impact on the static capacitance measured in a Crystal Impedance Meter is shown by Equations (10) and (11) below.

Grounded Cover:

$$C0(MEASURED) = C0 + C1 \quad \text{[Equation 10]}$$

Ungrounded Cover:

$$C0(MEASURED) = C0 + \frac{C1(C2+C3)}{C1+C2+C3}$$

IF C1 = C2 and 2C1 >> C3 then

$$C0(MEASURED) = C0 + 0.5\,C1 \quad \text{[Equation 11]}$$

Normally the stray capacitances (C1, C2) from the crystal electrodes to the crystal cover are approximately the same value. Twice this capacitance value is usually much greater than C3 capacitance term. These approximations allow the equation for the ungrounded condition to be simplified to that shown in Equation (11).

Equations (12) and (13) show the impact of the cover connection on the static capacitance measurement made in a Transmission System.

Grounded Cover:

$$C0(MEASURED)=C0 \quad \text{[Equation 12]}$$

Ungrounded Cover:

$$C0(MEASURED)=C0+\frac{C1C2}{C1+C2+C3}$$

IF C1 = C2 and 2C1 >> C3 then

$$C0\ (MEASURED) = C0 + 0.5\ C1 \quad \text{[Equation 13]}$$

These equations are different from Equations (10) and (11) derived for the CI Meter. The difference in static capacitance measurements between a Crystal Impedance Meter and a Transmission System is shown by Equations (14) and (15).

$$C0(CIMETER\text{-}TRANSMISSION)=C1 \quad \text{[Equation 14]}$$

Ungrounded Cover:

$$C0(CIMETER\text{-}TRANSMISSION)=\frac{C1C3}{C1+C2+C3} \quad \text{[Equation 15]}$$

These capacitance terms for Crystal #10 of Table 1 were measured as: C1 = 1.08 pF, C2 = 1.08 pF, and C3 = 0.3 pF. Using these values, the correlation difference between a Transmission System and a CI Meter is 1.08 pF if the cover is grounded. The 1.08 pF can be converted to a correlation difference in load resonant frequency by multiplying by the trim sensitivity of the crystal. The trim sensitivity for Crystal #10 is 24.8 ppm/pF at 15 pF of load capacitance. The 1.08 pF difference, therefore, corresponds to a load resonant frequency difference of 26.8 ppm.

The ungrounded cover correlation difference defined by Equation (15) is only 0.13 pF (3.2 ppm). As this example illustrates, the load frequency correlation between Crystal Impedance Meters and Transmission Systems is better if the measurements are made with the crystal cover ungrounded.

Coupled Modes

A coupled mode of vibration is caused by a different vibrating mode of the crystal coupling into the standard mode of vibration. These coupled modes are normally suppressed by the design of the crystal and are not commonly present in production crystals. The presence of a coupled mode in the frequency region bounded by the series resonant frequency of the crystal and the specified load resonant frequency can have a pronounced effect on the load resonant measurement. This effect was examined in previous paragraphs.

Crystal Spurious Responses

The crystal model shown in Figure 1 assumes a perfectly linear device. Unfortunately this approximation is not always a good one. A real crystal has several spurious frequencies that are greater in frequency but usually much less in activity than the load resonant frequency. If these spurious frequencies are close to the crystal resonance and relatively large in activity they can have an effect on load resonant measurements made with the "Calculated" Transmission System measurement method. A modified crystal equivalent circuit including the spurious responses is shown in Figure 15.

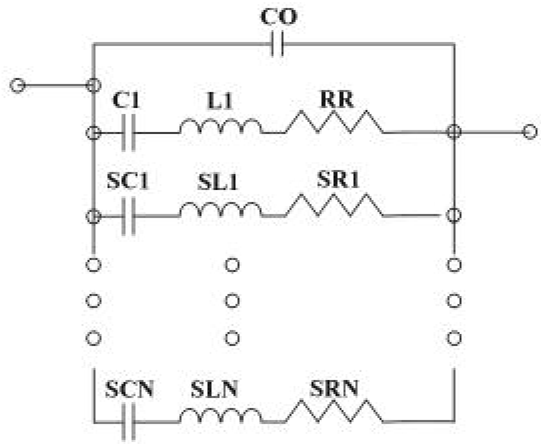


Figure 15

Where: SC1,SL1,SR1 = Capacitance, Inductance and Resistance of the first spurious
SCN,SLN,SRN = Capacitance, Inductance and Resistance of the N'th spurious

The impact of a spurious frequency on the load frequency measurement made with the "Calculated" method can be approximated as a capacitance error.

This offset can be calculated using Equation (16).

$$CE=\left[\frac{SC1\,FR}{2(SF1-FR)}+\cdots+\frac{SCN\,FR}{2(SFN-FR)}\right] \qquad \text{[Equation 16]}$$

Where: CE = Capacitance Error (pF)
SF1 = Spurious Frequency #1 (Hz)
SFN = Spurious Frequency #N (Hz)

An example crystal was selected to illustrate the impact of spurious frequencies. The activity response of this crystal is shown in Figure 16.

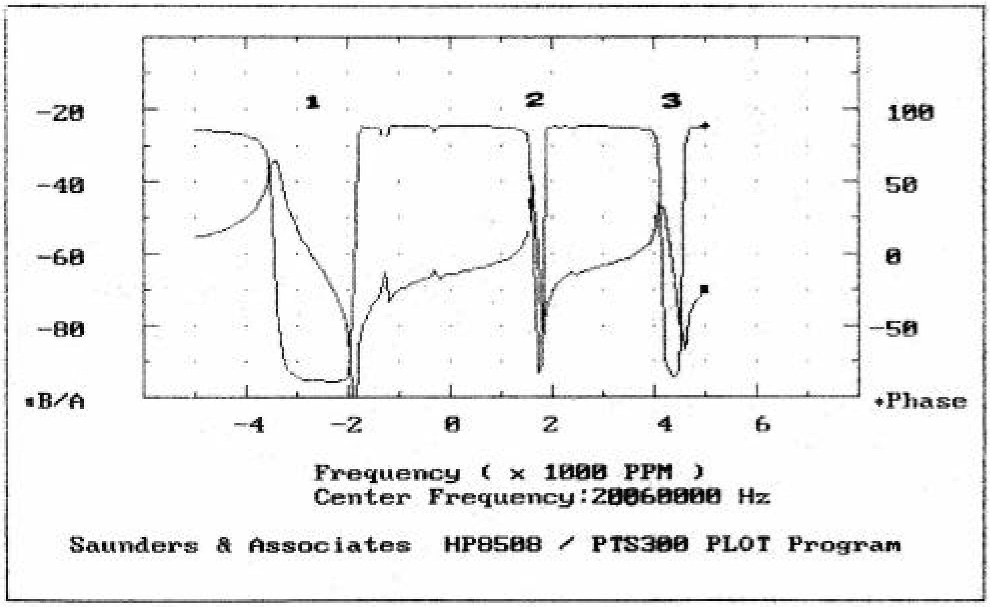


Figure 16

This graph shows the attenuation of the crystal in decibels as a function of frequency. The phase shift across the crystal is also displayed.

The frequency marked #1 is the series resonant frequency of the crystal. The frequencies indicated by #2 and #3 are the spurious frequencies whose impact on the "Calculated" load resonant frequency will be determined.

The motional parameters of each frequency were measured using a S&A 350A system. This information is contained in Table 2.

	FREQUENCY	C1	RR	C0	CL	TS
1	20000202	25.2	6.5	6.5	20	18
2	20091511	2.6	35.5			
3	20142364	4.4	27.3			

Table 2

Using Equation (16), the impact of the two spurious frequencies on the "Calculated" load frequency measurement is 0.58 pF. This corresponds to a frequency difference of 10.4 ppm between the "Calculated" technique and the "Measured", "Physical Capacitor" or Crystal Impedance measurements.

The example crystal was selected because of its large spurious responses and large trim sensitivity. The impact of typical production crystals due to the spurious frequencies is usually minimal.

CONCLUSIONS

Transmission Systems and Crystal Impedance Meters can be used to measure the load resonant frequency of a quartz crystal. The interpretation of this measurement requires an understanding of the measurement method and the characteristics of the crystal.

The specification of load resonant frequency is better represented as a tolerance specified on load capacitance. The load capacitance specification reflects the impact of the crystal and the specified load capacitance on the sensitivity of the load resonant measurement.

Crystal Impedance Meters provide a cost effective method of measuring load resonant frequency. The CI Meter uses a physical capacitor to make the load resonant measurement. If the specified load capacitance is different than the physical capacitor, a mathematical correction can be done to obtain the desired load frequency.

Transmission Systems can measure the load resonant frequency using three distinct methods; "Calculated", "Measured", and "Physical Capacitor".

The "Calculated" method measures the crystal at series resonant frequency and mathematically calculates load resonant frequency. This method can be used if the response of the crystal is well known or precise measurements are not required. The "Calculated" method is susceptible to load frequency errors due to nonlinear crystal responses.

The "Measured" method first measures the crystal in the same manner as the "Calculated" method then makes a correction based upon an impedance measurement at the calculated load resonant frequency. The "Measured method works best for those crystals with a load resonant impedance less than 1000 ohms. The measurements made include the impact of any nonlinear crystal responses.

The "Physical Capacitor" technique uses an actual capacitor inserted in the PI Network to make the load resonant measurement. This method provides a better resolution of load frequency measurement than the "Measured" and "Calculated" methods. The "Physical Capacitor" method also does not limit the drive current available to the crystal. The motional parameters must be mathematically corrected for the stray capacitances of the test socket. The value of these strays must be well known and constant in order to make accurate measurements.

The crystal spurious responses can impact the load resonant measurement made on a Transmission System using the "Calculated" method. In the example presented, the "Calculated" method resulting in a load frequency error of 0.58 pF (10.4 ppm) when compared to the measurements made with other methods.

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