17

Circuitry Frequency Stability Requirements in Crystal Oscillators, Excluding the Crystal

17.1 INTRODUCTION[17.1]

This chapter considers the crystal oscillator as a system composed of several subsystems. The subsystems must be completely specifiable as regards inputs, outputs, interfaces, and performance.

Preferably, the subsystem stability performance should be describable in the same terms as those of the system. Frequently this is impossible, undesirable, or inconvenient. In that case, relationships, preferably simple, should be established between the terms of the subsystem performance and the terms of the system performance.

This chapter identifies the minimum subsystems present in all crystal oscillators, and, indeed, in all oscillators, and relates the stability of each subsystem to the total oscillator stability.

All crystal oscillators are made up of at least two distinct subsystems.

1 The crystal resonator hereafter also called the osci (see Section 1.3.1, item 1).
2 The remaining circuitry, hereafter called the llator.

It would be very desirable to evaluate the stability of each one independently. In the present state-of-the-art, it is not feasible to simply and completely evaluate the crystal by itself, although extensive work has been carved out by Walls, Wainwright, and others to independently determine the crystal short-term performance.[3.44, 3.59] However, it turns out that the llator is readily amenable to such evaluation and that quantitative limits can be set for the performance of the llator, relative to the oscillator performance, under certain operating conditions of the llator and the crystal described later.

This chapter develops the approximate relations between the oscillator and llator performance for a given crystal and describes the experimental technique for measuring the llator performance. The derivation is relatively simple but it yields considerable information concerning the design of oscillators and the measurement of the llator performance.

It should be noted that the material in this chapter is particularly applicable to the medium and long-term frequency stability but does include some treatment of the short-term stability.

The llator evaluation is useful for the three following broad categories of applications:

1 *In new designs*, it permits the budgeting of the llator for an overall oscillator stability performance and the experimental confirmation of whether the budget is being met.

2 *In old designs*, or in manufacture of oscillators based on already available designs, the situation often arises where the oscillator performance is unsatisfactory and the crystal designer is convinced that the fault lies in the circuitry, while the circuit designer is equally convinced that it is a crystal problem. At present, the solution for this dilemma has been to replace the crystal and/or circuitry until satisfactory performance has been achieved, usually at great cost of time and money. The llator evaluation procedure would markedly facilitate the resolution of this problem.

3 It provides information on the crystal stability performance.

17.2 THE OSCI AND LLATOR CONCEPTS (*See Section 1.3.1, Item 1*)

Figure 17.1 shows the block diagram of a typical oscillator using the llator concept. It is seen that it consists of only two subsystems:

1 The osci.
2 The llator.

In a crystal oscillator, the osci would be a crystal. In a noncrystal harmonic oscillator, the osci would be a resonator or part of a resonator. The llator is the

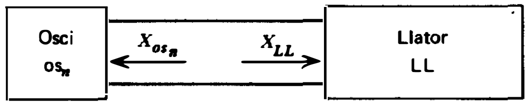

Figure 17.1 Oscillator block diagram.

rest of the oscillator including the oven and any other means for maintaining the electrical, mechanical, and thermal environments.

A very important and necessary condition for the llator evaluation is that the osci is considered "perfect," meaning that the osci is completely stable, that is, independent of the environment and time; this condition can usually be practically satisfied during the time necessary for measuring the llator performance.

Obviously the total instability of the actual oscillator is the sum of the llator instability and the actual osci instability. Conversely, the instability of the osci is the difference between the actual oscillator instability and instability of the llator referred to the perfect osci.

It is noted from Fig. 17.1 that the osci has associated with it a reactance X_{os} which is a function of only the operating frequency, f. Also the llator has associated with it a reactance, X_{LL}, which is a function of not only the physical reactances in the llator but also includes the contribution of the active circuitry and the environmental conditions.

17.3 OSCILLATOR RELATIONSHIPS USING THE OSCI LLATOR CONCEPT

For a given osci, os_n, and a llator, LL, in Fig. 17.1

$$\frac{\Delta f_{\mathrm{os}_n}}{f} = \frac{\Delta f_{\mathrm{os}_n}}{\Delta X_{\mathrm{os}_n}} \cdot \frac{\Delta X_{\mathrm{os}_n}}{f} \tag{17.1}$$

and from Eq. (1.48)

$$X_{\mathrm{os}_n} = -X_{\mathrm{LL}} \tag{17.2}$$

from which

$$\Delta X_{\mathrm{os}_n} = -\Delta X_{\mathrm{LL}} \tag{17.3}$$

for

$$\begin{gathered} \Delta f \lll f \\ f \text{ can be assumed constant} \end{gathered} \tag{17.4}$$

Equation (17.3) states that any ΔX_{LL} produced by instability of the llator will be counterbalanced by an equal $-\Delta X_{\mathrm{os}_n}$ which thus produces a $\Delta f_{\mathrm{os}_n}/f$ in accordance with Eq. (17.1).

If the osci is made to be a crystal, then in accordance with Section 3.2

$$\Delta X_{\mathrm{xtal}} \approx 2 Q_{\mathrm{xtal}} R_{\mathrm{xtal}} \frac{\Delta f_{\mathrm{xtal}}}{f} \tag{17.5}$$

so that from Eqs. (17.3) and (17.5),

$$\frac{\Delta f_{\text{xtal}}}{f} \approx \frac{\Delta X_{\text{LL}}}{2Q_{\text{xtal}} R_{\text{xtal}}} \tag{17.6}$$

17.4 CRYSTAL OSCILLATORS WHEREIN THE CRYSTAL NETWORK OPERATES IN THE INDUCTIVE REGION

Consider an oscillator wherein the crystal network operates within its inductive region, such as the Pierce oscillator and investigate the effect of replacing the crystal with the perfect os_2 shown in Fig. 17.2.

L in os_2 is chosen so that the frequency of oscillation is approximately that of the crystal oscillator.

Obviously,

$$X_{\text{os}_2} = 2\pi L f \tag{17.7}$$

and

$$\Delta X_{\text{os}_2} = 2\pi L \, \Delta f_{\text{os}_2} \tag{17.8}$$

so that from Eqs. (17.2), (17.3), (17.7), and (17.8)

$$\frac{\Delta f_{\text{os}_2}}{f} \approx \frac{\Delta X_{\text{LL}}}{X_{\text{LL}}} \tag{17.9}$$

Combining Eq. (17.5) and (17.9),

$$\frac{\Delta f_{\text{os}_2}}{f} = \frac{-\Delta f_{\text{xtal}}}{f} \cdot \frac{2Q_{\text{xtal}} R_{\text{xtal}}}{X_{\text{LL}}} \tag{17.10}$$

or the converse

$$\frac{\Delta f_{\text{xtal}}}{f} = \frac{-\Delta f_{\text{os}_2}}{f} \frac{X_{\text{LL}}}{2Q_{\text{xtal}} R_{\text{xtal}}} \tag{17.10a}$$

The significance of Eq. (17.10) is illustrated by the following examples:

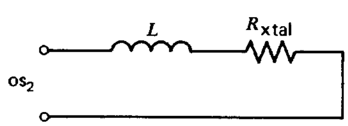

Figure 17.2 Osci os_2.

Example 1

$Q_{\text{xtal}} = 100{,}000$, $R_{\text{xtal}} = 20\ \Omega$, $X_{\text{LL}} = -100\ \Omega$ and $\Delta f_{\text{xtal}}/f$ desired $= 10^{-9}$, then

$$\frac{\Delta f_{\text{os}_2}}{f} = 4 \times 10^{-5}$$

Example 2

$Q_{\text{xtal}} = 2 \times 10^{6}$, $R_{\text{xtal}} = 100\ \Omega$, $X_A = -400\ \Omega$ and $\Delta f_{\text{xtal}}/f$ desired $= 10^{-12}$, then

$$\frac{\Delta f_{\text{os}_2}}{f} = 10^{-6}$$

It is interesting to note from Eq. (17.10) that for maximum permissible llator instability, Q_{xtal} and R_{xtal} should be maximized and X_{LL} should be minimized. It follows that, for equal Q_{xtal}, the crystal with greater R_{xtal} (which is equivalent to smaller motional capacitance C_1) will permit greater llator instability. Example 2 demonstrates the severe requirements imposed on the llator. This is emphasized by noting that the Q of the oscillator with os_2 is less than 4 for a stability of 10^{-6}, an achievement which offhand appears impossible but direct experiment has proven to be feasible, a fact corroborated by the existence of crystal oscillators having stabilities better than 10^{-12}.

17.5 EXPERIMENTAL PROCEDURE FOR THE OSCILLATOR OF SECTION 17.4

An oscillator is available with known crystal parameters and a required stability. The problem is to determine whether the llator is adequate for this required stability.

The procedure is as follows:

1 Remove the crystal.

2 Replace the crystal by os_2 making R the same as R_{xtal} and making L a value which will yield approximately the same operating frequency. This is facilitated by determining the value of X_{LL} with the H.P. 4815 Vector Impedance Meter and calculating and trimming L until the right frequency is obtained. When the oscillator is energized, the current in os_2 should be approximately the same as in the crystal. os_2 is realized by a stable inductor in series with a resistor and this normally is a relatively easy procedure, provided that care is taken to maintain the environmental conditions for os_2 constant. The oscillator output frequency is then monitored by a frequency counter and the stability $\Delta f_{os_2}/f$ determined. The resolution of the counter need not be very high since a relatively unstable oscillator frequency is being measured.

3 The value of $\Delta f_{os_2}/f$ determined above is compared against that called for by Eq. (17.10). It if is less, then the llator is satisfactory. Otherwise efforts should be exerted to improve it as necessary.

17.6 CRYSTAL OSCILLATORS WHEREIN THE CRYSTAL NETWORK OPERATES NEAR SERIES RESONANCE

In this oscillator, the osci should take the form shown in Fig. 17.3. L_1 and C_1 are tuned to the approximate operating frequency.

For this osci in the region of series resonance,

$$\Delta X_{os_3} = 2Q_{os_3}R_{xtal}\frac{\Delta f}{f} \tag{17.11}$$

where

$$Q_{os_3} = \frac{X_{C_1}}{R_{xtal}} \tag{17.12}$$

and Eq. (17.10a) becomes, for this osci,

$$\frac{\Delta f_{xtal}}{f} = \frac{\Delta f_{os_3}}{f}\frac{Q_{os_3}}{Q_{xtal}}$$

The rest of the analysis and the measurement procedures are the same as for os_2.

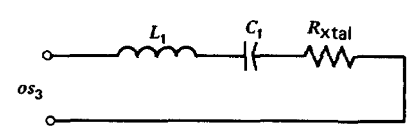

Figure 17.3 Osci os_3.

17.7 EXPERIMENTAL DETERMINATION OF THE OSCILLLATING POINT IN THE OSCILLATOR USING THE OSCI AND LLATOR CONCEPTS

Following the procedure described in Section 19.8, the llator impedance, $Z_{LL} = R_{LL} + jX_{LL}$, is measured at the nominal I_x and operating frequency. When $-R_{LL}$ is plotted against $-X_{LL}$ a curve, similar to that shown in Fig. 17.4*a*, is obtained. An approximation for this curve can be calculated from Eq. (5.38) wherein $-R_{LL}$ and $-X_{LL}$ are functions of the parameter g_m.

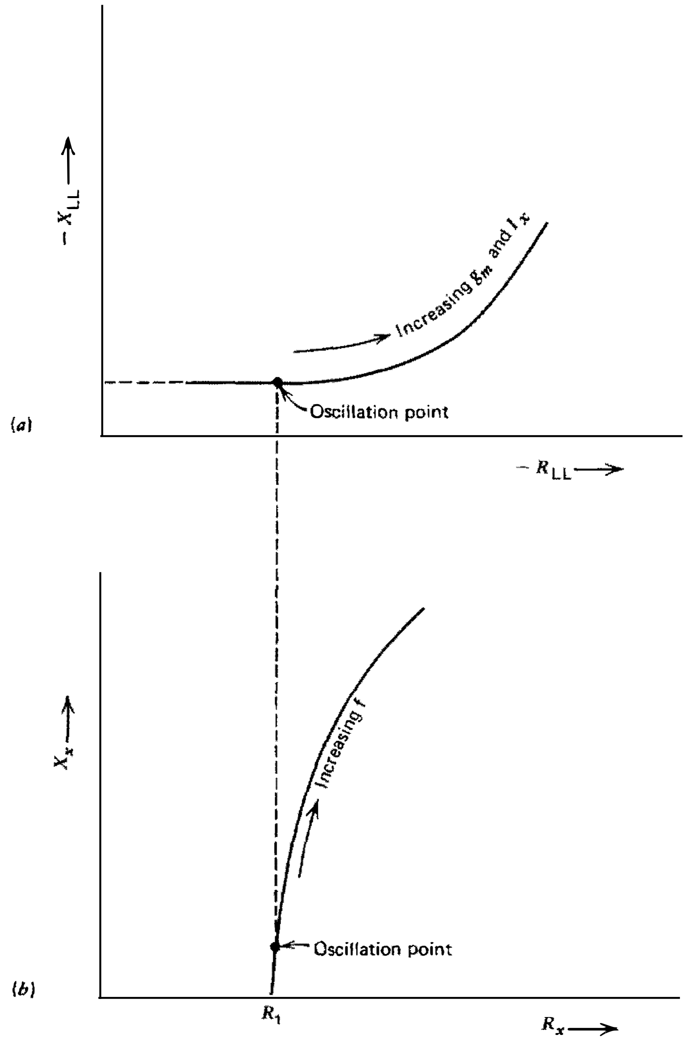

Figure 17.4 Determination of the point of oscillation. (*a*) X_{LL} versus R_{LL}. (*b*) X_x versus R_x.

Another curve of R_x versus X_x can be obtained for the crystal by measurement or by calculation from the material in Chapter 3. A typical curve is shown in Fig. 17.4*b*.

When the two curves are superimposed, it is seen that oscillation occurs where R_x coincides with $-R_{LL}$, in the flat region of $-X_{LL}$. The corresponding X_x is then read off Fig. 17.4*b* and the operating frequency computed from the crystal characteristics.

17.8 CONDITIONS FOR THE APPLICABILITY OF SECTIONS 17.1 TO 17.7

The material presented thus far is only applicable to the medium- and long-term frequency stability since the analysis does not include the crystal filtering action and the additive phase noises such as those described in Section 14.3.2 and Fig. 14.3.

Also, some practical problems are created during the analysis and measurement procedures when the crystal is replaced by another osci which markedly decreases the oscillator operating Q. Among these problems are the following:

1 The analysis does not take into consideration the C_0 of the crystal.

2 During the measurement procedure, some spurious oscillation, because of the new osci, may be caused and must be suppressed. A greater problem is that the oscillator may squegg because the shorter time constant of the new osci may be smaller or the same order of magnitude of the other time constants in the oscillator, thus causing squegging. This squegging will not exist in the actual oscillator because of the very high Q of the crystal which produces a much larger time constant. The squegging may be corrected by changing some of the time constants in the oscillator biasing and filtering circuits (see Section 18.4).

17.9 SHORT-TERM PERFORMANCE

The long-term performance has been described, up to now, in the time domain. However, the short-term performance is more conveniently analyzed in the frequency domain. After the analysis has been completed the results may be translated into the time domain. Also, it may be more convenient to obtain the raw experimental data in the time domain; the data will then require translation into the frequency domain.

When analyzing the short-term performance the noise contributions of many more subsystems require consideration. Among these subsystems are the ALC amplifiers (if present), the output amplifiers, the oven (if any), and the power supply.

An approximate evaluation of the circuit noise $S_{\phi_g}(\mathbf{f})$ can be obtained by replacing the crystal with a type os_3 osci (see Fig. 17.3). The operating Q, Q_{os_3}, and the $S_\phi(\mathbf{f})$ of the oscillator with the os_3 osci are measured.

$S_{\phi_g}(\mathbf{f})$ is then computed by means of the converse of Eq. (14.17) or (14.20), as applicable.

Knowing the Q_{os_3}, the oscillator operating Q with the crystal can be computed from the crystal parameters. The $S_\phi(\mathbf{f})$ of the oscillator with the crystal is then computed from Eq. (14.17) or (14.20) as applicable.

It should be remembered that the above procedure will yield only the $S_\phi(\mathbf{f})$ of the oscillator for the case where the crystal is considered perfect; that is, the crystal itself does not generate significant noise and does not exhibit frequency changes due to change in time or environment.