4
Oscillator Frequency Stability

The term *frequency stability* is a generic term which means a variety of things to different people depending on their individual interests. In its broadest concept, it means the degree of constancy of the frequency of an oscillator under a particular set of conditions. In crystal oscillator applications, there are several different types of frequency stability:

a. Frequency stability as affected by environmental changes consisting primarily of temperature, voltage, and load variations.
b. Long-term frequency drift as affected by aging of the quartz crystal resonator.
c. Short-term frequency stability or phase stability.

Frequency stability is used in this book to mean either a or b, both of which will be discussed in this chapter. In some specifications frequency stability is meant to be the sum of a and b; however, because so much misunderstanding has resulted, it is recommended that when this usage is adopted it should be clearly stated that frequency stability is meant to include both environmental stability and aging for a specified time period. The term frequency accuracy is also sometimes specified and is a measure of the actual frequency compared to an established standard. It results from the initial setting error and the stability.

4.1. TEMPERATURE EFFECTS ON FREQUENCY

The frequency of a crystal oscillator is affected by changes in ambient temperature. These changes in temperature can affect the value of any of the components which comprise the oscillator circuit. If these component variations do not cancel each other, a change in the nominal operating frequency of the oscillator will result. The frequency determining component most severely affected by any temperature change is the quartz crystal. This effect is shown graphically for AT-cut crystals in Chapter 5, Figure 5-6. (A discussion of the temperature coefficients of other crystal cuts can be found in reference 6.)

In some applications, sufficient frequency stability can be obtained from the quartz crystal. The limit obtainable over the full military temperature range of -55°C to +105°C with an AT-cut crystal is approximately ±0.002 percent. This limit can be improved within a reduced temperature range. Many applications require stabilities considerably better. In such cases, two methods are available for eliminating or reducing the effects of temperature changes on the crystal oscillator, namely, temperature control and temperature compensation.

4.1.1. Temperature Control

The degree of temperature control required on a particular oscillator is determined primarily by the specifications of the system in which it is to be used. Stabilities of approximately ±5 parts in 10^7 can be obtained using plug-in crystal ovens with the oscillator circuitry external to the oven. Stabilities to several parts in 10^9 can be obtained with proportionally controlled ovens containing the crystal and oscillator circuitry. (A proportionally controlled oven uses a temperature-controlling system in which the power supplied to the oven is proportional to the heat loss. (Refer to section 9.3.) For stabilities better than 5 parts in 10^9, it is generally necessary to use a two-stage oven. This may be a combination of two ovens with a single control circuit or two independent proportionally controlled ovens.

Crystal ovens have several disadvantages which tend to limit their usage in some applications. These are as follows:

1. A warm-up time is required.
2. The volume is relatively large.
3. The power consumption is high.
4. The reliability of the components in the oven is reduced if the application requires frequent turning on and off of the oven.

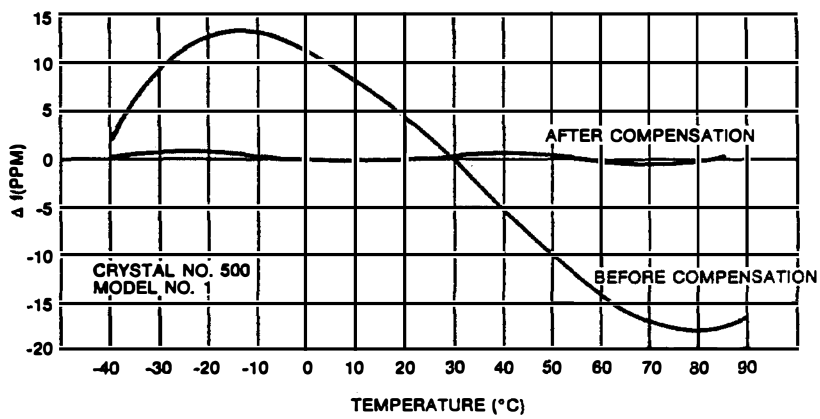

Figure 4-1. Frequency versus temperature characteristic for a typical temperature-compensated crystal oscillator.

4.1.2. Temperature Compensation

Temperature compensation of crystal oscillators is very practical to achieve frequency stabilities in the range of ±10 to ±0.5 ppm. With considerable care, compensation to ±0.05 ppm is possible.

Temperature compensation is generally achieved by placing a voltage variable capacitor in series with the crystal. A voltage is then applied to the capacitor, which pulls the crystal frequency by precisely the amount that it drifted in temperature but in the opposite direction. The voltage is generated either by a thermistor-resistor analog network or by a digital system followed by a digital-to-analog converter.

The means for temperature compensation are discussed in considerable detail in Chapter 10. Figure 4-1 shows the improvement in frequency that was achieved using a three-thermistor analog network in a 3.2-MHz crystal oscillator.

4.2. LONG-TERM FREQUENCY DRIFT

The phrase *long-term frequency drift* usually refers to the gradual drift in average frequency of an oscillator due to aging of components, notably the quartz crystal. It is not meant to include the short-term variations discussed in section 4.3 or the deviations due to ambient temperature change discussed in section 4.1. The aging of a quartz crystal itself is discussed in section 5.7.

4.3. SHORT-TERM FREQUENCY STABILITY

The phrase *short-term frequency stability* refers to changes in the oscillator frequency which result from interaction of the desired signal with an unwanted signal or noise. It is not meant to include frequency variations due to component aging or ambient temperature change. The type of interaction may be simple superposition, amplitude modulation, frequency modulation, phase modulation, or any combination thereof. Only in the case of FM or PM is there a true change in frequency. The other types may cause an apparent change in frequency which may vary with different frequency-measuring techniques. For this reason, the signal-to-noise ratio or sideband level of an oscillator is sometimes specified. If phase modulation is the only type of interaction being considered, or is predominant, the term *phase stability* may be used in place of short-term frequency stability. Frequency modulation and phase modulation are related by the modulation frequency. If the undesirable signal is sinusoidal, this relationship is given by

$$\Delta\theta = \frac{\Delta f}{f_m}$$

where $\Delta\theta$ is the peak phase deviation in radians, Δf is the peak carrier frequency deviation, and f_m is the frequency of the undesirable signal.

As is the case of any FM or PM signal, theoretically an infinite number of sidebands exist. The total phase deviation is usually so small with crystal oscillators, however, that only the first pair of sidebands is significant. The relationship between these sidebands and the phase deviation is given in Figure 4-2. This graph does not consider the presence of AM. The mathematical development of Figure 4-2 is given in Appendix J. In the case of noise modulation, the sideband levels are often specified in decibels below the carrier per hertz of bandwidth (dB/Hz). For a narrow-bandwidth measurement system, pure FM or PM noise modulation results in the same sideband level as shown in Figure 4-2. Here the sideband level is in-

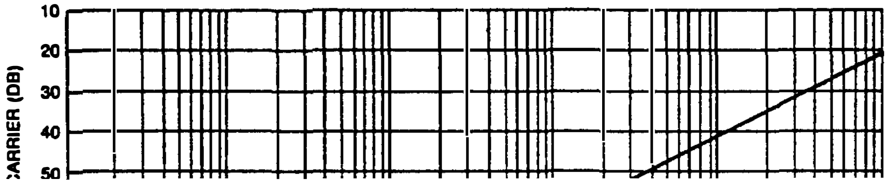

Figure 4-2. Sideband level versus phase deviation.

terpreted to be the ratio of the rms value of the noise sideband to the rms value of the carrier, and the abscissa is $\sqrt{2}$ times the rms phase deviation. For noise simply added to the signal, the sidebands are uncorrelated and the apparent phase deviation is 3 dB lower for the same sideband level. The rms phase jitter is then given by $\Delta\theta = 10^{-dB/20}$ rad rms, where dB refers to the level of either the upper or lower sideband in a bandwidth numerically equal to the baseband in which the phase jitter is measured.*

In many cases short-term frequency stability is best specified in the time domain and is given as the rms fractional frequency deviation for some specified measurement time τ. For example a precision crystal oscillator might exhibit a short-term stability of 1×10^{-11} rms for one-second averaging times. If a large number of frequency measurements, say n, are made using an averaging time of τ seconds, the standard deviation can be computed using the statistical relationship

*Short-term frequency stability and/or phase noise can be conveniently measured using a phase-locked loop with two identical oscillators, with a spectrum analyzer, a computing frequency counter, or a frequency stability analyzer.

$$\sigma_n^2(\Delta f) = \frac{1}{n-1}\left[\sum_{i=1}^{n}(f_i)^2 - \frac{1}{n}\left(\sum_{i=1}^{n} f_i\right)^2\right]. \tag{4-1}$$

It has been found, however, that for large numbers of measurements, the elapse time is so large that frequency aging and temperature effects tend to influence the results and σ becomes a function of how long the test was run. A better method and one which has become standard is to use the Allan variance. In using this method individual variances are computed from adjacent pairs of frequency readings and the average of the variances forms the basis for the definition. Taking $n = 2$, equation (4-1) simplifies to

$$\sigma_2^2(\Delta f) = \frac{(f_1 - f_2)^2}{2}. \tag{4-2}$$

The frequency stability is then found by taking the square root of the average of the variances, and is

$$\sigma_y(\tau) = \left[\frac{1}{2N}\sum_{i=1}^{N}(f_{2i} - f_{2i-1})^2\right]^{1/2} \tag{4-3}$$

where τ is the measurement time for each frequency reading with no dead time between readings, and N is the number of measurement pairs used. A fairly large number of readings is required to compute a reliable value of $\sigma_y(\tau)$, and $N = 100$ is quite common.

The time domain method of specifying short-term frequency stability is useful for counting intervals ranging from less than a millisecond to about 100 seconds. It is possible to convert from time domain measurements to frequency domain performance and vice versa. Indeed this is a very powerful method of determining the frequency spectral content of an oscillator within a fraction of 1 Hz of the carrier.[51] In general, however, it is best to specify the characteristic which is actually important to the system. For example if it is the phase stability that is important than this should be specified.

The art of designing oscillators for best short-term frequency stability is not treated in this book; however, it should be pointed out that it is a very important consideration in the design of some oscillators. A rigorous definition of short-term frequency stability is itself quite complex, and the reader is referred to reference 52 for a comprehensive treatment of the subject.