19

Component and Circuitry Measurements

19.1 INTRODUCTION

To facilitate oscillator circuit design, troubleshooting, and trimming, it is absolutely necessary to have full knowledge of the characteristics of the components and circuitry at the operating frequency.

Too often, component characteristics are only approximately known from sketchy catalogue information and guesswork. In particular, guessing is intolerable in oscillator design and, for that matter, in any type of design.

In addition to component characteristics, it is also required to determine the magnitudes of the voltages and currents at the different circuit points. Knowledge of these magnitudes is essential for the following purposes:

1 Troubleshooting.
2 Circuit trimming.
3 Adjusting circuit networks to precalculated values.
4 Gathering data for recordkeeping which will be useful for later design, maintenance, and troubleshooting.

It can be categorically stated that the industry has been remiss in performing adequate recorded measurements during the design and production phases in the mistaken belief that such measurements consume unnecessary time and expense. This is extremely false economy and results in

1 Marginal and often more expensive designs.
2 Inability to duplicate performance in another but supposedly identical unit.

3 Excessive production problems.
4 Difficulty in later repair because of the lack of reference data.

The types of measurements considered in this chapter are:

1 dc voltage, current, and resistance.
2 ac current and voltage at the oscillator operating frequency.
3 Linear component and small-signal immittances at the oscillator operating frequency.
4 Large-signal immittance and phase at the oscillator operating frequency.

19.2 GENERAL CHARACTERISTICS OF THE MEASUREMENT PROCEDURES

1 The measurements should be performed at the oscillator operating frequency.
2 The measuring devices should not excessively load the circuit being measured; that is, the magnitude does not change markedly upon connecting the measuring device to the measured point.
3 The accuracy should be adequate for the intended purpose. In general, $\pm 5\%$ is sufficient for most measurements but it should be checked that greater accuracy is not required.

19.3 dc MEASUREMENTS

19.3.1 Voltage

dc voltages are usually measured with a voltmeter having a dc input resistance of at least 10 MΩ. Therefore the dc loading is normally negligible. However, the ac loading due to the capacitance of the voltmeter and its leads may be large and will markedly change the ac voltages existing at the measuring points. This, in oscillators, may cause a significant change in the dc voltage and result in a serious error in the voltage measurement. As shown in Fig. 19.1, R_{IS} are provided to minimize the effective dc loading due to the ac loading.

The resistors, R_{IS}, are low-capacitance ($< \frac{1}{2}$ pF) isolating elements inserted in series with the voltmeter leads *at the measuring points*. Their resistance may be 100 kΩ which will reduce the 10 MΩ input resistance voltmeter reading by about 1% for each isolating resistor for which a correction may be made in the final voltmeter reading. If one lead is connected to a point having no ac signal present, its R_{IS} may be omitted.

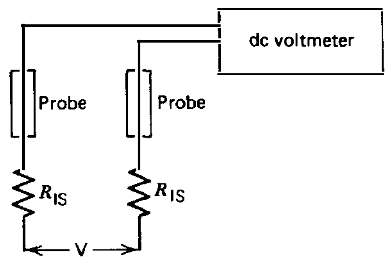

Figure 19.1 Setup for dc voltage measurements.

19.3.2 Current

In most cases, the current can be determined by measuring the voltage drop across a known resistance as described above and then computing the current. In those cases where this is not feasible the clip on dc milliammeter is recommended.

19.3.3 Resistance

The most convenient insrument for measuring dc resistance at reasonable accuracy is the digital volt-ma-ohmmeter. Of course, the oscillator must be deenergized when the measurements are being made. Also, in many cases, one of the leads of the device being measured must be disconnected for meaningful readings.

19.4 ac VOLTAGE AND CURRENT MEASUREMENTS

Often these measurements are difficult to make without significantly loading the circuit being measured, particularly at very high frequencies. Therefore the discussion of these measurements includes means of minimizing the loading.

19.4.1 ac Voltage Measurements

The most suitable instruments for these measurements are the high-impedance RF millivoltmeters with an input capacitance of less than 2 pF. When higher voltages are to be measured, the same instrument should be used with suitable multipliers.

In many cases, a meter input capacitance of even only 2 pF will cause considerable mistuning. If, in those cases, a tapped-down point is available, the ratio, n, between the readings of the two points should be determined by using two similar meters simultaneously, as shown in Fig. 19.2. Obviously, the V_2 reading will be more accurate because of the lower source impedance level. Once n is determined, only V_2 is measured and V_1 is computed using the relationship

$$V_1 = nV_2 \tag{19.1}$$

In making the measurements, the location of the voltmeter ground terminal on the device being measured is very critical, particularly for low voltages at high frequency because of ground signal couplings.

The above measurements are based upon the premise that one of the device measuring points is ground. In those cases where the voltage between two nonground points is required, the only practical method is to take measurements between each point and ground, using a vector voltmeter (see Section 19.6) and then to compute the voltage between the two points.

In interpreting the voltmeter readings, it should be kept in mind that the response of the meter is strongly dependent upon the wave form being measured, and different voltmeter designs may have different wave-form responses which may also be functions of the magnitude of the signals. The vector voltmeter is unique in that it responds only to the fundamental component of the signal.

Another point to consider is that the voltmeter input impedance is often a function of the signal magnitude.

19.4.2 ac Current Measurements

This is a relatively difficult measurement to make but fortunately there are few cases where ac current measurements are required.

In many cases, the current can be determined by measuring the voltage drop across a known impedance and then computing the current (see, e.g., Section 7.7.1).

If the current cannot be measured as described above, a current probe in combination with a millivoltmeter or oscilloscope must be used. Commercial current probes are available for the entire useful frequency range. However, a common problem is that it is difficult to insert the current probe because of the size of the clip-on jaws of the probe. It is, therefore, recommended that permanent half-loops of sufficient size be provided at those points where the current is likely to be measured.

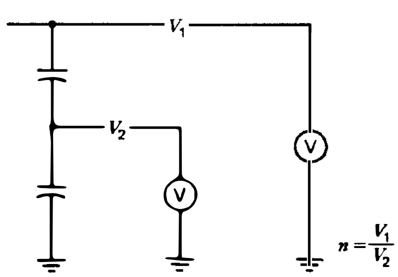

Figure 19.2 Setup for ac voltage measurements where a tapped point is available.

19.5 THE OSCILLOSCOPE AS A MEASUREMENT TOOL

One of the most useful instruments for electronics measurement is the oscilloscope. This section discusses the precautions that must be taken for its use in oscillators. These precautions are the same as when measuring other devices at high frequency and at high impedance points.

The oscilloscope should be used principally for wave-form observations and timing information. It should not be used for accurate measurements of amplitudes. The direct reading meter is more accurate, generally has higher input impedance, and is easier to use.

Extreme care should be taken that the oscilloscope probe does not load the circuit excessively. For that reason, the probe input impedance should be consistent with the type of measurement. In practice, many measurements made with an oscilloscope are excessively loaded by its probe impedance. The probe input impedance should be measured to ensure it is sufficiently high for the intended application. The manufacturer's specifications are usually optimistic.

19.6 LINEAR AND SMALL-SIGNAL IMMITTANCE MEASUREMENTS

This is a very important type of measurement as it provides the oscillator designer with much needed information on component and circuit behavior at the actual operating frequency and eliminates considerable guesswork and conjecture. It also facilitates the adjustment of the critical networks prior to activating the oscillator.

19.6.1 Necessary Characteristics of the Instrumentation

1 It should be easy to operate and be direct reading.

2 It should be capable of measuring in-circuit components and networks as well as out of circuit. To that end the measuring terminals or probe should be as small as possible and extremely portable to be able to gain access to the points being measured.

3 The instrumental signal level should be small to ensure small-signal operation.

4 It should have a wide frequency operating range. In addition, it is desirable that the frequency setting resolution be capable of being made extremely fine.

5 It should be capable of measuring a wide range of impedances in all four quadrants, that is, negative and positive reactance and resistance in all combinations.

6 It should be capable of measuring active circuitry for determining transistor characteristics.

7 It should have an accuracy of at least $\pm 5\%$.

The instruments having most of the above characteristics are the Hewlett Packard 4193A Vector Impedance Meter for frequencies from 0.4 to 110 MHz and the Hewlett Packard 4815A Vector Impedance Meter for frequencies from 0.5 to 108 MHz.

The instruments are quite similar except that the 4193A output data is presented in digital form, while the 4815A data is in analogue form. The digital presentation affords greater impedance resolution but not necessarily greater accuracy. The 4193A has considerably greater built-in frequency settability, resolution, and accuracy, but the 4815A frequency performance can be improved as desired by the addition of an external frequency source.

The instruments operate on the principle of injecting a constant current into the impedance being measured and displaying magnitude and phase of the resultant voltage drop across the impedance.

The instruments present the impedance data as $|Z|$, θ, and have the disadvantages that one terminal of the impedance being measured must be at ground potential and that the accuracy for the R component of high Q impedances is quite poor.

19.6.2 The Measurement of Passive Linear Components and the Small-Signal Characteristics of Nonlinear Components

These instruments are extremely useful for measuring the small-signal reactance and resistance characteristics of such components as resistors, capacitors, inductors, and voltage or current variable components such as varactors, pin diodes, Zener diodes, and other semiconductors, all at the frequency of operations.

19.6.3 Examples of Measurement of Active and Passive Networks in Oscillators

The impedance measurements which can be made with these instruments are very useful in both the design and production phases of oscillators.

Some examples are now given in the following subsections.

19.6.3.1 Measurement of the Small-Signal Llator Impedance, Z_{LL} (See Fig. 5.9)

The crystal or other osci, Z_3, is disconnected and the $|Z|$-θ meter connected in its place. The llator is energized, Z and θ are read, and the corresponding X_{LL}

and R_{LL} calculated. θ should be between $-90°$ and $-180°$ so that R_{LL} is negative. The small-signal $|R_{LL}| \geqq 2R_3$ for oscillation and proper limiting.

19.6.3.2 Adjustment and Checking of the Overtone and c Mode Selector (See Fig. 10.3)

With the oscillator deenergized, connect the $|Z|$-θ meter to the Q_1 emitter and to ground. The meter frequency is scanned across the oscillator frequency range and X_2 as read on the $|Z|$-θ meter should be as shown in Fig. 19.3.

19.6.3.3 Determination of Crystal Parameters

In this example the parameters of Fig. 19.3 are determined for a high Q crystal.

As the internal frequency generator is not sufficiently stable for this measurement, the $|Z|$-θ meter will be driven by a high-resolution frequency synthesizer controlled by a very stable oscillator, as shown in Fig. 19.4.

The measurements are performed as follows:

1 The frequency is set for $|Z|$ = min and $\theta = 0°$. The $|Z|$ reading is then R_1 and the frequency is f_s.

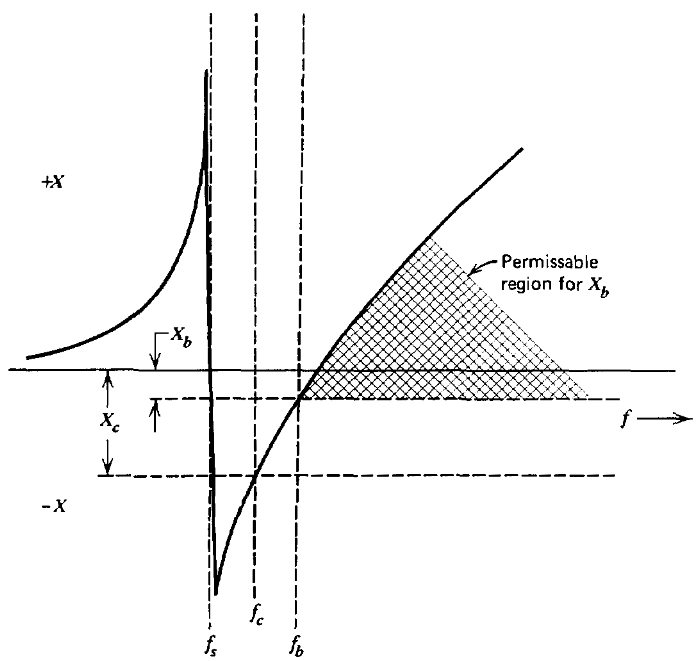

Figure 19.3 Relations for X_2 network for SC-cut crystal as measured by the $|Z| - \theta$ meter. *Notes*: (1) f_s is designed to be $0.75f_c$. (2) f_s should be $\geqq 0.70f_c$: critical for $N = 5$, noncritical for $N = 3$. (3) $X_b \leqq \frac{1}{4}X_c$.

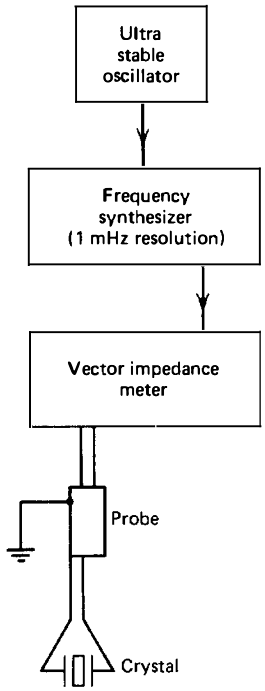

Figure 19.4 Test equipment setup for determining high Q crystal parameters.

2 The frequency is then changed slightly until $\theta = +45°$ and $f_{45°}$ noted.

3 The frequency is then adjusted so that $\theta = -45°$ and $f_{-45°}$ noted.

4 $$Q_x = \frac{f_s}{f_{45°} - f_{-45°}} \tag{19.2}$$

5 Knowing Q_x, f_s, and R_1, C_1, and L_1 are easily computed.

6 C_0 is obtained by shifting the frequency to $0.99f_s$, reading X_0, and then computing C_0.

It should be noted that the crystal must be protected against meaningful temperature changes during the measurement period.

Limitations of the above procedure are that the crystal drive cannot be varied and the measurements are performed at room temperature.

19.6.3.4 Measurement of Transistor Small-Signal Parameters

As pointed out in Chapters 2 and 5, the transistor small-signal parameters are extremely useful in determining the starting conditions for oscillation and also are the basis for the large-signal characteristics. It is therefore desirable to be able to simply obtain the parameters at the actual operating frequency, dc current, and dc voltage. This section demonstrates the procedures for determining many of the parameters using the vector impedance meter and accessory equipment.

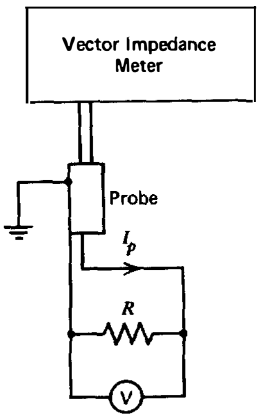

Figure 19.5 Test setup for measuring the probe current in the vector impedance meter.

Before starting the measurements it is necessary to know the actual probe current, I_p. This current is stated in the equipment specification but it is often incorrect, so it should be checked.

Figure 19.5 shows the equipment setup for determining I_p. The $|Z|$-θ meter is set to the desired frequency and a convenient resistor connected to the $|Z|$-θ meter probe in parallel with voltmeter V. $|Z|$ is read on the $|Z|$-θ meter and V on the voltmeter; then

$$I_p = \frac{V}{|Z|} \tag{19.3}$$

It will be found that I_p is fairly independent of the frequency but may be a function of the $|Z|$ range. (See the specifications for the applicable instrument.)

Figure 19.6 shows the equipment arrangement for measuring the small-signal parameters of transistor Q_1. In that figure, the 50-Ω resistor is provided for suppressing spurious oscillations and to enable the determination of the ac current I_c, with voltmeter V. r_{b_1} and r_{b_2} are selected so that their resistance $\ggg Z$ or its components.

It is obvious that

$$|I_c| = \frac{|V|}{50} \tag{19.4}$$

$$|V_b| = |Z||I_p| \tag{19.5}$$

therefore

$$|\beta| = \frac{|I_e|}{|I_p|} \approx \frac{|I_c|}{|I_p|} \tag{19.6}$$

$$|g_m| = |y_{21}| \approx \frac{I_c}{V_b} = \frac{|I_c|}{|I_p||Z|} \tag{19.7}$$

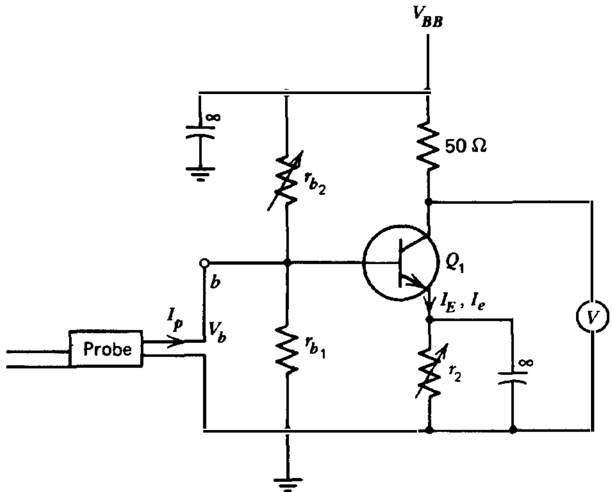

Figure 19.6 Test setup for measuring transistor parameters.

Z can be separated into two parallel components as shown in Fig. 19.7, where

$$r_{be} = \frac{|Z|}{\cos\theta} \tag{19.8}$$

$$X_{be} = \frac{|Z|}{\sin\theta} \tag{19.9}$$

$$C_{be} = \frac{159{,}000}{fX_{be}} \tag{19.10}$$

If

$$r_{bb'} \text{ is neglected,} \tag{19.11a}$$

and

$$\theta_{g_m} \text{ assumed } 0, \tag{19.11b}$$

then

$$g_{m_0} \approx |g_m| \tag{19.12}$$

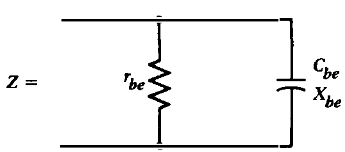

Figure 19.7 Separation of Z into r_{be} and X_{be} components.

and

$$\beta_o \approx g_{m_0} r_{be} \tag{19.13}$$

From Eq. (2.47),

$$f_T \approx \frac{159{,}000}{C_{be}} g_{m_0} \tag{19.14}$$

assuming $C_{bet} \lll C_{be}$. It should be noted that if V in Fig. 19.6 is made a vector voltmeter, then the assumptions in Eqs. (19.11) are not necessary and more accurate results may be obtained, but with more complicated equations.

It is obvious that additional parameters of the transistor can be obtained using procedures similar to those described above.

19.7 LARGE-SIGNAL IMMITTANCE AND PHASE MEASUREMENTS

The type of instrument most useful in the above class of measurements is the vector voltmeter such as the Hewlett Packard 8405A, combined with a suitable signal generator. Its frequency range of operation is 1 to 1000 MHz.

The voltmeter measures two voltages and the phase between them. One voltage is called Channel A and the other Channel B. There is a probe for each voltage. The instrument has two meters. One meter indicates the voltage of the channel selected by a manually operated switch on the meter front panel. The other meter reads the phase difference between the two. Obviously the two voltages must have the same basic frequency, otherwise their steady-state phase relationship cannot be displayed. The A channel is called the reference channel and should be connected to the signal which has the cleanest wave form. The meters respond only to the fundamental component of the signals. However, a jack is provided for viewing the signals translated to a 20-kHz carrier which has the same harmonic wave form (but not the noise) of the signals. The Channel A signal should have a relatively high signal-to-noise ratio.

The probe input capacitance is relatively high about 2.5 pF and therefore caution should be exerted that the probes do not excessively load the circuit under test.

Figure 19.8 shows the equipment setup for measuring the input impedance of the device under test (DUT), such as an amplifier. Transformer T1 and low value resistance R are used for obtaining the current flowing into the DUT. These two elements can be replaced by a suitable current probe feeding probe B. When using a current probe, due allowance should be made for the phase shift in the probe, which should be experimentally determined at each frequency of interest.

Obviously the voltage can be fed into any port and the current measured in the same or other port so that any type of immittance and/or phase relationship can be investigated. See, for example, Section 7.7.2.

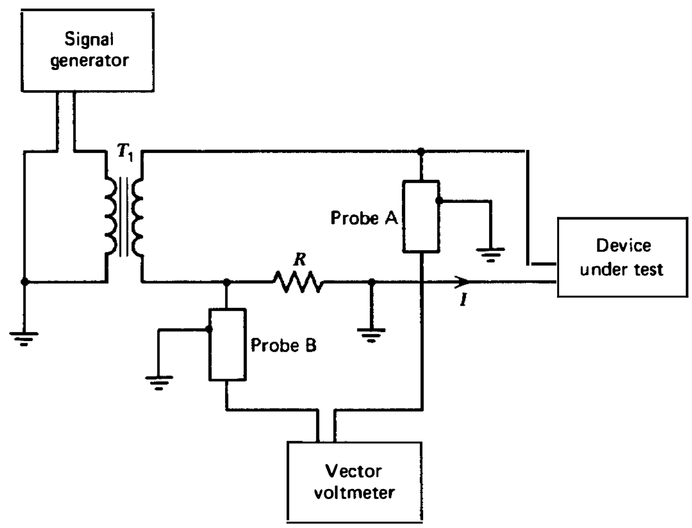

Figure 19.8 Test setup for measuring input impedance.

The above measurement technique has the important advantage that large signals can be impressed on the DUT and the fundamental component of all immittances and phase angles determined since, as previously pointed out, the meter readings are functions of only the fundamental components of the voltages fed to the vector voltmeter.

It should be noted that this setup can also perform the small-signal measurements, described in Section 19.5, but the Vector Impedance Meter is more convenient for that purpose.

19.8 Z_{LL} MEASUREMENT PROCEDURE

Section 19.7 and Fig. 19.8 describe a method of measuring the input impedance of a device (DUT). This device can be the llator of an oscillator. In that case the measurement is performed at the value of $I = I_x$, and Z_{LL} can thus be determined as a function of the frequency f and crystal current I_x.

The procedure described above is practical only when one terminal of the llator is at ac ground potential, as in the Colpitts oscillators. When both terminals are off ground, the indirect procedure described below may be used. This procedure is based upon Section 1.3.1.

The measurement setup is shown in Fig. 19.9. Y_1 is a crystal having a low value of R_L at its rated frequency f_L, which is the oscillator frequency when the crystal sees a llator reactance equal to the reactance of its rated load capacitance, C_L. R_v is a variable resistance and X_v is a variable reactance, which may be either inductive or capacitive depending upon the llator. R_v and X_v are adjusted until the oscillator frequency is f_L and the crystal current is the

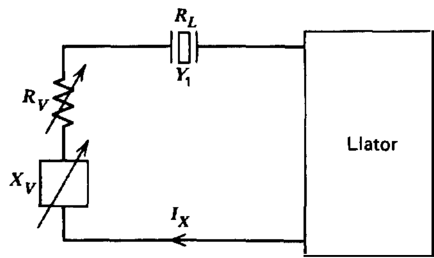

Figure 19.9 Test setup for measuring Z_{LL}.

desired current, I_x. Then, from Eqs. (1.47) and (1.48),

$$Z_{LL} = -(R_L + R_v) - j(-X_{C_L} + X_v) \tag{19.15}$$

Z_{LL} is thus obtained as a function of I_x. The crystal motional capacitance, C_1, should be relatively high so as to make $\partial f/\partial X$ relatively large.

Since it is very difficult to realize a suitable variable R_v at high frequencies, the procedure can be simplified if the crystal properties are well known. R_v can thus be a set of fixed resistors and f can be allowed to vary slightly since Z_{LL} is not a very sharp function of f, while Z_{Y_1} is a relatively sharp function.

If X_v is capacitive, then the llator has an L_{eq}.

$$L_{eq} = \frac{X_v}{2\pi f} \tag{19.16}$$

L_{eq} is a useful concept for most of the integrated circuit oscillators in Chapters 15 and 16.

If X_v is inductive, then the llator has a C_{eq}

$$C_{eq} = \frac{159{,}000}{f_L X_v} \tag{19.17}$$

C_{eq} is a useful concept for the *Pierce family* of oscillators described in Chapter 5.

An alternative modification of the procedure described above is to eliminate Y_1. R_v and X_v are then adjusted until the desired f and I_x are obtained. Equation (19.13) becomes

$$Z_{LL} = -(R_v + jX_v) \tag{19.18}$$

The latter procedure appears preferable because of its relative simplicity. However, its use may be impractical in many crystal oscillators, particularly of the self-limiting type, because of the possible spurious oscillations and squegging as described in Section 17.8.