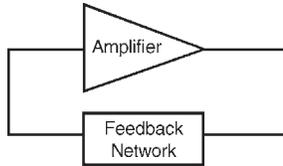# OSCILLATOR
THEORY OF OPERATION

Crystal controlled oscillators may be considered as consisting of an amplifier and a feedback network that selects a part of the amplifier output and returns it to the amplifier input. A generalized depiction of such a circuit is shown below.

Figure 1.0

In order for an oscillator circuit to operate, two (2) conditions must be met:

   (A) The loop power gain must be equal to unity.
   (B) The loop phase shift must be equal to 0, 2Pi, 4Pi, etc. radians.

The power fed back to the input of the amplifier must be adequate to supply the oscillator output, the amplifier input, and to overcome circuit losses.

The exact frequency at which an oscillator will operate is dependent on the loop phase angle shifts within the oscillator circuit. Any net change in phase angle will result in a change in the output frequency. As the usual goal of an oscillator is to provide a frequency that is essentially independent of variables, some means of minimizing the net phase shift must be employed. Perhaps the best, and certainly the most common means of minimizing the net phase shift is to use a quartz crystal unit in the feedback loop.

The impedance of a quartz crystal changes so dramatically with changes in the applied frequency that all other circuit components can be considered as being of essentially constant reactance. Therefore, when a crystal unit is used in the feedback loop of an oscillator, the frequency of the crystal unit will adjust itself so that the crystal unit presents a reactance which satisfies the loop phase requirements. A depiction of the reactance vs. frequency of a quartz crystal unit is shown below.

Figure 2.0
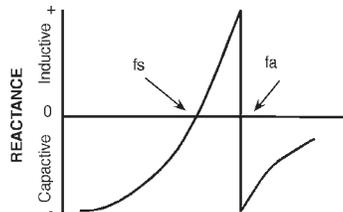
As is apparent from Figure 2.0, a quartz crystal unit has two frequencies of zero phase. The first, or lower of the two, is the series resonant frequency, usually abbreviated as Fs. The second, or higher of the two frequencies of zero phase is the parallel, or anti-resonant frequency, usually abbreviated as Fa. Both the series and parallel resonant frequencies appear resistive in an oscillator circuit. At the series resonant point, the resistance is minimal and the current flow is maximal.

At the parallel point, the resistance is maximal and the current flow is minimal. Therefore, the parallel resonant frequency, Fa, should never be used as the controlling frequency of an oscillator circuit.

A quartz crystal unit can be made to oscillate at any point along the line between the series and parallel resonant points by the inclusion of reactive components (usually capacitors) in the feedback loop of the oscillator circuit. In such a case, the frequency of oscillation will be higher than the series resonant frequency but lower than the parallel resonant frequency. Because of the fact that the frequency resulting from the addition of capacitance is higher than the series resonant frequency, it is usually called the parallel frequency, though it is lower than the true parallel frequency.

Just as there are two frequencies of zero phase associated with a quartz crystal unit, there are two primary oscillator circuits. These circuits are generally described by the type of crystal unit to be used, namely "series" or "parallel."

SERIES CIRCUIT:

A series resonant oscillator circuit uses a crystal which is designed to operate at its natural series resonant frequency. In such a circuit, there will be no capacitors in the feedback loop. Series resonant oscillator circuits are used primarily because of their minimal component count. These circuits may, however, provide feedback paths other than through the crystal unit. Therefore, in the event of crystal failure, such a circuit may continue to oscillate at some arbitrary frequency. A depiction of a basic series resonant oscillator circuit is given below.

Figure 3.0
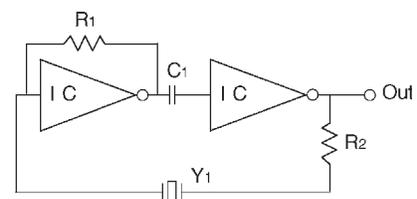
As is apparent from Figure 3.0, a series resonant oscillator circuit provides no means of adjusting the output frequency, should adjustment be required. In the above circuit, resistor R1 is used to bias the inverter and to cause it to operate in its linear region. This resistor also provides negative feedback to the inverter. *Capacitor C1* is a coupling capacitor, used to block DC voltage. *Resistor R2* is used to bias the crystal unit. This resistor strongly influences the drive current seen by the crystal unit, therefore care must be taken that too small a value is not chosen. *Crystal unit Y1* is a series resonant crystal unit, specified to operate at the desired frequency and with the desired frequency tolerance and stability.

OSCILLATOR
THEORY OF OPERATION

PARALLEL CIRCUIT:

A parallel resonant oscillator circuit uses a crystal unit which is designed to operate with a specified value of load capacitance. This will result in a crystal frequency which is higher than the series resonant frequency but lower than the true parallel resonant frequency. These circuits do not provide paths other than through the crystal unit to complete the feedback loop. In the event of crystal unit failure, the circuit will not continue to oscillate. A basic depiction of a parallel resonant circuit is given below.

Figure 4.0
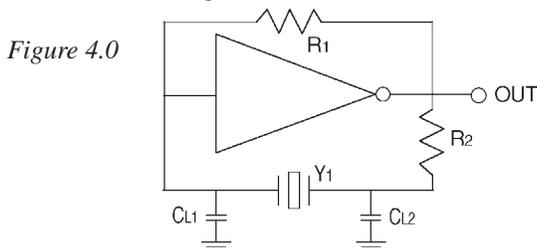
This circuit uses a single inverter, with two capacitors in the feedback loop. These capacitors comprise the "load capacitance" and together with the crystal unit, establish the frequency at which the oscillator will operate. As the value of the load capacitance is changed, so is the output frequency of the oscillator. Therefore, this circuit does provide a convenient means of adjusting the output frequency, should adjustment be required.

The resistors R_1 and R_2 serve the same functions as detailed for the series resonant circuit shown in Figure 3.0. The two load capacitors, C_{L1} and C_{L2}, serve to establish the frequency at which the crystal unit and therefore the oscillator will operate. Crystal unit Y_1 is a parallel resonant crystal unit, specified to operate with a specified value of load capacitance, at the desired frequency and with the desired frequency tolerance and stability.

LOAD CAPACITANCE:

Reference has been made to a "specified value of load capacitance." Load capacitance may be defined as "that value of capacitance, either measured or calculated, present in the oscillator circuit, across the connection points of the crystal." In the case of a series resonant circuit, there is no capacitance present between the connecting points of the crystal unit and therefore, load capacitance need not be specified for a series resonant crystal unit. In the case of a parallel resonant oscillator circuit, capacitance is present. As a direct measurement of this capacitance is impractical, it is usually necessary to calculate the value. The calculation of the value of the load capacitance is done with the following equation:

$$C_L = \frac{C_{L1} * C_{L2}}{C_{L1} + C_{L2}} + C_S \qquad (1)$$

Where C_{L1} and C_{L2} are the load capacitors and C_S is the circuit stray capacitance, usually 3.0 to 5.0 pF.

It must be noted that changes in the value of the load capacitance will result in changes in the output frequency of the oscillator. Therefore, if precise frequency control is required, then a precise specification of load capacitance is required. To illustrate, assume that a crystal unit is specified to operate at a frequency of 20.000 MHz with a load capacitance of 20.0 pF. Assume that the crystal unit is then placed in a circuit which presents a value of 30.0 pF. The frequency of the crystal unit will then be lower than the specified value. Conversely, should the circuit in question present a value of 10.0 pF, the frequency will be higher than the specified value. The relationship between frequency and load capacitance is shown below.

Figure 5.0
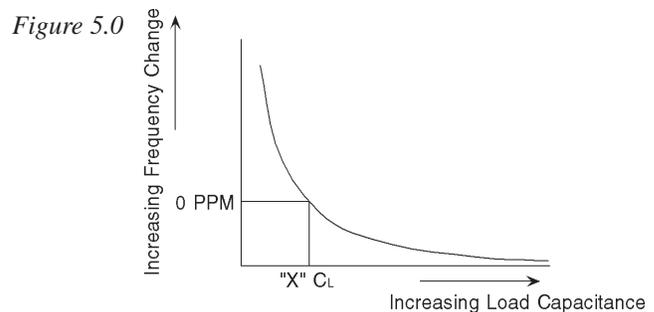
DRIVE LEVEL:

The "drive level" is the power dissipated by the crystal unit while operating. The power is a function of the applied current, and is usually expressed in terms of Milliwatts or Microwatts. Crystal units are specified as having certain <u>maximum</u> values of drive level, which change as functions of the frequency and mode of operation. It is well to consult with the crystal unit vendor as to the maximum value of drive level allowed for a particular crystal unit. Exceeding the maximum drive level for a given crystal unit may result in unstable operation, increased aging rates, and in some cases, catastrophic damage. The drive level may be calculated by the following equation:

$$POWER = (I_{rms}^2 * R) \qquad (2)$$

Where *I* is the *rms* current through the crystal unit and R is the maximum resistance value of the specific crystal unit in question. Equation (2) is simply "Ohms law" for power.

Measurement of the actual drive level in an operating oscillator circuit may be accomplished by temporarily inserting a resistor in series with the crystal unit. The resistor must be of the same ohmic value as the crystal unit. The voltage drop across the resistor may then be read and the current and power dissipation calculated. The resistor must then be removed. As an alternative means of measuring the drive level, a current probe may be used at the output lead of the crystal unit, if space permits.

OSCILLATOR
THEORY OF OPERATION

FREQUENCY VS OVERTONE MODE:

The frequency of a quartz crystal unit is limited by the physical dimensions of the vibrating quartz element. In some cases, the limiting dimension(s) are the length and width. In the case of the most popular crystal unit, the "AT" cut crystal unit, the limiting dimension is the thickness of the vibrating quartz element. As the thickness is diminished, the frequency is increased. At some point, usually around 30.000 MHz, the thickness of the quartz plate becomes too thin for processing.

Should it be desired to develop an oscillator at a frequency higher than the limiting frequency, advantage must be taken of the fact that quartz crystal units will oscillate at odd integer multiples of their "fundamental" frequency. We may define the "fundamental" frequency as "that frequency which naturally occurs at a given set of mechanical dimensions." Therefore, if a crystal unit has a fundamental frequency of 10.0 MHz, it can also be made to oscillate at 3, 5, 7, etc. times the fundamental. That is, the unit will oscillate at 30.0, 50.0, 70.0, etc. MHz. These multiples of the fundamental frequency are called "overtones" and are identified by the integer of multiplication, as in the "third overtone", the "fifth overtone", etc. When use at an overtone frequency is required, the crystal unit must be specified to operate at the desired frequency and on the desired overtone. One should never attempt to order a fundamental mode crystal unit and then operate it at an overtone frequency. This is so due to the fact that the crystal manufacturing processes differ for fundamental and overtone crystal units.

In many cases, the characteristics of the integrated circuit used in a particular oscillator design dictate that the fundamental frequency of the crystal unit be suppressed in order to ensure operation at the desired frequency and on the desired overtone. In such cases, it is usually necessary to modify the oscillator circuit. One method of modification is to add a "tank" circuit, consisting of an inductor and a capacitor. These modifications are shown in *Figure 6.0* and *7.0*
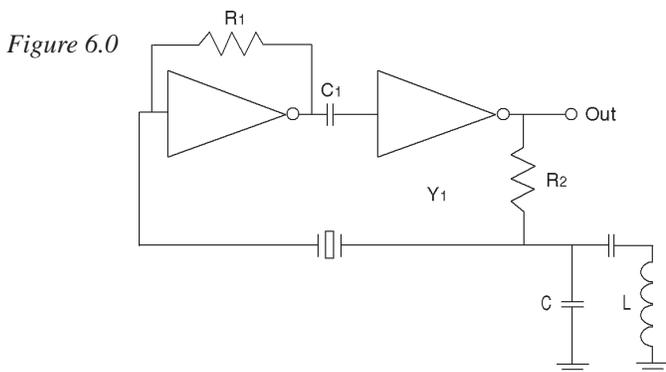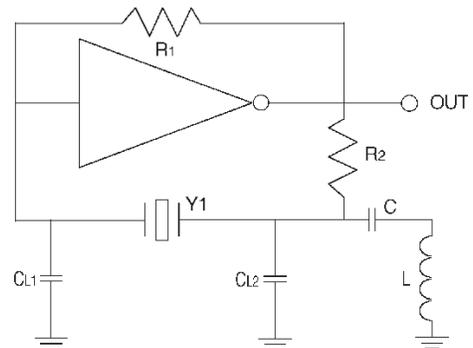
Figure 6.0

Figure 6.0 depicts the modification of a series resonant circuit while *Figure 7.0* depicts the modification of a parallel resonant circuit.

Figure 7.0

In both cases, the tank circuit is tuned to resonate at some frequency between the fundamental and the desired frequency. This results in the unwanted frequency being shunted to ground, leaving only the desired frequency being present at the output of the oscillator.

DESIGN CONSIDERATIONS:

For good operation of an oscillator circuit, certain design considerations should be followed. In all cases, it is recommended that parallel traces be avoided in order to reduce circuit stray capacitance. All traces should be kept as short as possible and components should be isolated in order to prevent coupling. Ground planes should be used to isolate signals.

NEGATIVE RESISTANCE:

For optimum performance, an oscillator circuit must be designed in such a way as to enhance "negative resistance," which is sometimes called the "oscillation allowance." Evaluation of the amount of negative resistance in a given circuit is accomplished by temporarily installing a variable resistor in series with the crystal unit. The resistor should be set initially at its lowest setting, preferably close to zero ohms. The oscillator is then started and the output monitored on an oscilloscope. The variable resistor is then adjusted so that resistance is increased while the output is continuously monitored. At some value of resistance, oscillation will be stopped. At this point, the variable resistor is measured to determine the ohmic value at which oscillation ceased. To this value, the maximum resistance of the crystal unit, as specified by the vendor, must be added. The total ohmic resistance is deemed to be the "negative resistance" or the "oscillation allowance." For good, reliable circuit operation, it is recommended that the negative resistance be a minimum of five times the specified maximum resistance value of the crystal unit.

Values of negative resistance exceeding five times the maximum resistance of the crystal unit are better yet. As negative resistance tends to decrease at elevated temperatures, it is recommended that the test be performed at the highest temperature of the operating range.