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Guide for the Use of Quartz Crystal Units for Frequency Control

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TABLE OF CONTENTS

LIST OF TABLES

GUIDE FOR THE USE OF QUARTZ CRYSTAL UNITS FOR FREQUENCY CONTROL

1. INTRODUCTION AND SCOPE

This document has been compiled in response to a generally expressed desire on the part of both users and manufacturers for a guide to the use of quartz crystal units for frequency control so that they may be used to their best advantage. The most common error has been the assumption on the part of some users that the crystal unit is an absolute frequency-determining device. This idea has persisted, probably due to the fact that the frequency tolerances in earlier equipment were sufficiently wide that frequency variation imposed by the associated circuit conditions were small enough to be ignored.

It is not the function of this brief document to explain theory nor to attempt to cover all the eventualities which may arise in practical circumstances. It does draw attention to some of the more fundamental questions which should be considered by the user of quartz crystal units for new applications. Such a procedure will reduce considerably the user's risk of unsatisfactory performance.

1.1 GENERAL

Although the performance of a quartz crystal unit depends mostly on its design and fabrication its performance is influenced by other circuit components associated with it. For example, small variations in the input impedance of the oscillator circuit may result in modification of the frequency of oscillation beyond the permissible limits.

The quartz crystal unit is a mechanical vibrating system which is driven by the electrical current supplied to it. The amplitude of the vibration is proportional to the current. If the amplitude is great enough the quartz will fracture resulting in catastrophic failure. Heat is generated in the quartz as it vibrates. The resulting rise in temperature is proportional to the square of the current. Driving the unit at levels higher than the specified value may result in excessive frequency changes.

An even more serious problem is the effect of thermal gradients in the quartz. These may result from excessive drive levels or from external heat sources such as the heaters in ovens. The thermal gradients produce stresses in the quartz which may result in very large frequency perturbations.

High drive levels also tend to create or aggravate coupled modes resulting in changes in the parameters of the crystal unit and in undesired responses.

Since temperature and thermal gradients influence the frequency of a crystal unit some time is required for the frequency to become stable after turn-on. The time required depends upon the design and the drive level. Ordinarily the frequency becomes substantially stable after a few minutes of operations. Sometimes permanent changes in the frequency occur, especially after the unit has been operated at a high drive level. Effects of this nature may result from various causes. For example: internal fractures in the quartz caused by excessive strain, loss of electrode metal due to the acceleration forces which may well exceed a million times that of gravity, permanent displacement in the crystal lattice of the quartz, inelastic properties of the mounting systems, displacement of dust particles on the surface of the quartz, etc.

Sometimes the equivalent resistance of a crystal unit is found to change with the drive level. This phenomenon is particularly common in units designed to be operated at very low drive levels. It is thought to be due, in most cases, to surface effects such as loose plating or particles of some foreign material on the surface of the quartz. Although a crystal unit should be operated at the drive level for which it was designed, any change of resistance with drive level is usually an indication of inadequate processing technique.

Whenever possible the oscillator circuit should be designed to utilize a standard crystal unit and care should be taken to insure that the crystal unit is operated at its rated drive level.

In special cases where no standard crystal unit is available, the circuit designer should work closely with the crystal manufacturer to insure that the crystal unit and the circuit are compatible and that the resulting circuit meets customer's requirements.

Standard specific crystal data sheets, similar to those given in military documents such as MIL-C-3098, and supplier's technical information bulletins will define the available combinations of frequency tolerances, temperature range and load capacitance, the overtone order in the case of overtone crystals, and whether for series resonant or positive reactance operation. Each sheet will further specify the maximum level of drive and maximum equivalent series resistance (ESR) in relation to the frequency of the crystal unit. These data sheets have been carefully complied to include a wide range of crystal units with standardized performances and dimensions. It cannot be stressed too greatly that the user should, whenever possible, select his crystal units from these data sheets, even at the expense of circuit modifications, to permit the use of standard crystal units.

Standardization is a continuing process and, as new requirements arise, new data sheets will be produced to meet these requirements.

1.2 Technical Preamble

At frequencies near that of a mechanical resonance, a crystal unit may be represented by the equivalent electrical circuit of Figure 1 which consists of capacitance C_1, inductance L_1, and resistance R_1 in series, shunted by a second capacitance C_e due to the electrodes on the crystal plate. Always present are the distributed capacitances shown between terminals and metal holder (or ground if a non-metallic holder is employed). The first three parameters C_1, L_1, and R_1 are termed the "motional parameters" of the crystal unit. The resulting shunt capacitance C_o must be determined by considering C_e together with the distributed capacitances. For example, if the metal holder is grounded, some of the distributed capacitance will not appear across the "motional arm".

The circuit of Figure 1 accurately represents the crystal unit if the four parameters C_1, L_1, R_1 and C_o are constant. Changes in temperature, drive level or mechanical or thermal stresses may result in small changes in the value of the parameters. If the frequency of some extraneous mode of vibration happens to be equal to that for which the unit is designed, the two modes influence each other; i.e., are said to be "coupled". The presence of a coupled mode causes large variations in the motional parameters which are no longer independent of frequency and Figure 1 does not accurately represent the crystal unit. In this case the equations and measuring methods normally used do not apply. The validity of the circuit representation can be determined by measuring and plotting the impedance or admittance of the crystal unit as a function of frequency.

In a well designed and fabricated crystal unit the values of the motional parameters of the equivalent circuit are independent of the amplitude. An increase in the value of R_i as the drive level is decreased, or failure of the unit to "start" at low drive levels is an indication that sufficient care has not been exercised in the fabrication of the unit. Unfortunately, measurements of R_i at low drive levels are not always repeatable because the vibration of the quartz redistributed the offending surface material. The maximum tolerable variation in the value of R_i should be specified.

Frequency-temperature characteristics are, to a first approximation, determined by the temperature coefficients of the density, the dimensions, and the elastic modulus of the quartz plate. When the resultant of these three properties becomes zero, the stability of the frequency with respect to temperature will be optimum. A major part of the design consists of achieving this optimum condition over a specified range of temperature.

The frequency generated by a given crystal unit varies slightly with the impedance presented to it by the circuit (usually called "the load capacitance"). This effect may be useful or troublesome depending on the application. The frequency may be "trimmed" slightly by varying the load capacitance but inadvertent changes in the load capacitance may cause undesired changes of the frequency. The frequency stability with respect to differing load capacitance is determined largely by the capacitance ratio C_o/C_i. A crystal unit with large capacitance ratio is said to be a "stiff" crystal unit; i.e., its frequency changes little with variations of the input impedance, and vice versa.

Some crystal units exhibit large increases in the value of R_i at certain temperatures; the unit may even fail to operate. The increase of R_1 is usually accompanied by perturbations of the frequency. The phenomenon is termed "an activity dip". It is caused by coupling between two modes of vibration which happen to have the same frequency at a certain temperature. The problem is especially acute in units in which the ratio of the lateral dimensions of the blank to its thickness is too low. Since the thickness is determined by the frequency and the lateral dimension by the holder dimensions, it is sometimes difficult, or even impossible, to fabricate low frequency units in small holders. The customer should consult the crystal unit supplier before designing around units in which the diameter/thickness ratio is less than about 20. If low frequency is required one should consider going to the Tuning Fork or Strip AT design to avoid the above problem.

It will be readily understood in view of the comments made so far, that it is in the interests of manufacturers and users equally, to decide upon a suitable design of crystal unit in terms of the users requirements, using data sheets as a basis. Questions of availability of crystal units to the chosen specifications may modify, to some extent, the users original requirements.

2. CRYSTAL HOLDER CLASSIFICATION

Some or all of the following information will normally be given on the crystal unit:

- Frequency
- Manufacturer's name and code
- EIA code and/or manufacturer's catalog or type number
- Any other information necessary to obtain a complete definition of the crystal unit
- At the option of the manufacturer or by special request by the purchaser, a serial number and date of manufacture may be added
- Date code (week and year)
- User's part number

2.1 HOLDERS

Standard outlines of crystal holders are given in EIA-RS-192 and IEC Publications 122-3.

2.1.1 CATEGORIES OF HOLDERS

Holders generally fall into one of four classes:

a) Hermetically sealed glass or ceramic units
b) Hermetically sealed metal cases using glass-to-metal seals for the terminations or cold welded seals
c) Plastic cases
d) Surface mount packages

Glass envelopes are usually evacuated and metal types with reliable seals may be evacuated. This gives increased Q particularly at low frequencies, and improved long term frequency stability.

The most popular type of holder is the hermetically sealed metal case. The trend is towards the use of the smaller types of these holders, although it should be borne in mind that crystal units of a given type in the smaller holders usually demand lower drive levels than those in the larger ones.

Phenolic holders are adequate for the use in dry temperate conditions, but are not suitable for more severe climatic conditions since they are not impervious to moisture, nor can they be effectively sealed. These holders should not be considered where a protected environment is required.

2.1.2 NON-STANDARD HOLDERS

For certain important, though not widespread, applications; e.g., limited production of specialized types, non-standard holders have to be used. In these cases, individual agreement will have to be reached between customer and manufacturer.

2.2 CRYSTAL CONNECTIONS

There are currently no rules or standards that apply to pin connections of crystal units.

2.3 MOUNTING

Crystal units in general are capable of withstanding a specified amount of shock and vibration, but it must be realized that low-frequency crystal units will, in general, be more fragile than those of higher frequency of the same cut.

For nodally-mounted low-frequency units, it is the practice to support plates or bars from one or more pairs of wires bonded to the resonator surfaces at nodes or on a nodal line. These nodal regions are small, and damping due to the mounting is especially severe for the smaller plates. At the lower end of the frequency range, the mass and inertia of the resonator increase and satisfactory performance under severe shock and vibration is difficult to maintain.

Low-frequency crystal units may often be unusable in mobile applications unless special precautions are taken to protect the crystal units from shock and vibration. The characteristics of low-frequency units are appreciably influenced by the mounting and the effects of changes of temperature are likely to be evident, particularly on the increased resistance at an elevated temperature.

Recent developments in Strip AT crystal units and Tuning Forks make crystal units of the above mentioned design less desireable and should be avoided if possible. Strip AT's and Tuning Forks are good low frequency resonators and should be used for high vibration and shock applications.

High-frequency crystal units above 800 kHz vibrating in thickness shear, tend to oscillate largely within the center portion of the plate. This tendency is encouraged by the designer by contouring and restricting the electrode to the center of the crystal plate. Wire or ribbon suspensions to the relatively inactive edge areas of the plate are used for support and electrical connection. Where severe shock and vibration requirements are met, stiff mounting of the plate is employed. In general, the long-time drift rate may be increased due to strain relaxation of the support system. Crystal units with this type of mounting have been widely used with excellent results.

Basic mounting arrangements for four types of resonators are shown in Figure 2.

3. FREQUENCY

3.1 MODES OF VIBRATION AND FREQUENCY RANGES

The frequency range covered commercially by quartz crystal units may be taken as a few hundred Hz to over 150 MHz. Use is made of several cuts and modes of vibration (see Figure 3). The designation of certain quartz crystal "vibrators" with some of their principal characteristics are summarized on Table 1.

The approximate value of resonant resistance for these "vibrators" for some typical crystal units designs is shown in Figure 18.

TABLE 1

"Vibrator" Designation	Usual Description	Mode of Vibration	Usual Frequency Range	Approx. C_o/C_i
J	+5 X Duplex	Flexural	0.2- 10 kHz	200
K	+5 XY Bar	Flexural	2 - 16 kHz	500
H	+5 X Plate	Flexural	8 - 100 kHz	250
N	NT	Flexural	8 - 100 kHz	900
E	+5 X Plate	Extensional	40 - 200 kHz	130
C	Ct	Face Shear	150 - 750 kHz	350
D	DT	Face Shear	100 - 500 kHz	400
G	GT	Extensional	90 - 250 kHz	350
B	BT	Thickness Shear (Fundamental)	3000- 40000 kHz	650
A	AT(see note)	Thickness Shear (Fundamental)	800- 25000 kHz	250
A,B	AT or BT	Thickness Shear nth overtone (n= 3,5,7 ect.	15000- 150000 kHz	
	IT or SC	Thickness Sheer)	Same as AT or BT	

Note: Crystal units employing " A Vibrators" can also be produced in the range 400-800 kHz, but usually require larger than normal enclosures.

The ratios C_o/C_i quoted above are average values. The minimum value of the capacitance ratio is determined by the physical properties of quartz but units may be designed to have larger values. Unless the value of the capacitance ratio is specified, large variations in the value may be anticipated. For some applications the effects of these variations may have to be considered when using crystal units for which the C_o/C_i ratio is not specified (see Sub-sections 5.3 and 6.3). It should be clear that crystal units produced by a number of manufacturers may differ in certain respects. There may be differences in the equivalent network parameters. This may be very important in some applications, for example, keying, high drive conditions, and cases where frequency "pulling" is in use. This is one of the reasons why the prospective user is asked to give full details of his requirements (see Section 6).

Where crystal units are required of a particular type outside the frequency ranges listed on the applicable data sheet, special arrangements will have to be made with the manufacturer. A similar situation may arise with respect to the newer types of "vibrators" for which complete information is not available at the time of publication.

3.2 OVERTONE CRYSTAL UNITS

3.2.1 GENERAL

It is possible to excite vibrations in a quartz plate at frequencies which are (approximately) odd integral multiples of the fundamental frequency. An important example of this possibility is the excitation of the third, fifth, seventh (odd orders only), etc., overtones of the high-frequency thickness-sheer AT, SC, or BT cut plates; thus, if a crystal unit were designed for operation at 60 MHz on its third overtone, it would also be capable of vibrating in its fundamental mode at 20 MHz, its fifth harmonic overtone mode at 100 MHz, its seventh harmonic overtone node at 140 MHz, etc. It should be noted that the frequencies of the harmonic overtone modes are almost, but not exact, integral multiples of the fundamental frequency.

3.2.2 CHARACTERISTICS

A few important characteristics of high-frequency overtone crystal units must be kept in mind when designing oscillators using them.

a) Their application generally requires the use of an oscillator with a bandwidth sufficiently narrow to exclude the fundamental and other overtone frequencies of the unit, as well as adjacent modes such as the b-mode in the SC-cut crystal.

b) Since most overtone crystal units, particularly above the third, are specified for operation at series resonance, every attempt should be made to insure that the oscillator used will in fact oscillate the crystals at series resonance (see Section 5.2.2). If this is impossible, discussion with the manufacturer will usually result in a satisfactory solution.

c) It is to be clearly understood that operating a crystal unit at say 48 MHz on its third mechanical overtone is quite different from operating a fundamental crystal at 16 MHz and selecting the third harmonic, electrically produced by the oscillator. There is no signal anywhere in the circuit at 16 MHz or the higher overtone crystal frequencies; there will generally, of course, be the normal range of harmonics generated in the oscillator circuit at 96, 144 MHz, etc.

d) The properties of overtone crystal units as regards frequency vs. temperature and other characteristics can be suited to most requirements by correct design; however, the properties of a given crystal for a given order of overtone are quite different from those for its fundamental frequency or other orders of overtone, so that no reliance can be put on the behavior of a crystal unit at any frequency other than that for which it was designed.

e) The high-frequency overtone units have the same order of mechanical and climatic stability, aging, etc., as the similarly made fundamental units.

f) Frequency pulling can be achieved by connecting a variable reactance in series with the crystal unit (See Section 6.3). Caution: Inductance gives added resonance at a higher frequency and should, in general, be avoided. This does not occur when a capacitance is used.

4. FREQUENCY-TEMPERATURE DEPENDENCE

Quartz is the preferred material for use in making resonators for the control of frequencies because it has a suitable piezoelectric effect and is physically and chemically very stable. Furthermore, resonators in which the frequency is substantially constant over short ranges of temperature can be fabricated from quartz by orienting the quartz vibrator at specific angles with respect to the crystallographic axes of the quartz crystal. Formally natural quartz was used exclusively but today most of the quartz that is processed is "man-made", or cultured.

In the use of temperature controlled crystal units, the design of the oven may introduce temperature gradients within the quartz plate. These temperature gradients may cause excessive frequency shifts resulting in the oscillators frequency going outside its tolerances, although the operating temperature of the oven and other operating conditions are within their specified limits. This effect is minimized by using SC-cut resonators.

Similar considerations may apply if a non-temperature controlled unit is placed adjacent to a heat source. This subject may be studied in more detail by reference to the bibliography.

4.1 PARABOLIC CURVES

Many frequency-temperature characteristics conform fairly closely to the parabolic form:

$$\frac{df}{f} = -a_2(T_0 - T)^2$$

where df/f is fractional frequency difference, expressed in parts per million (ppm) between temperatures T and T_o.

T_o is the temperature at which maximum frequency occurs (turnover temperature)

T is any temperature in the operating range

a_2 is the constant of the parabola

Figure 4 shows the form of representative frequency-temperature curves of the BT, CT, and DT cuts.

The manufacturer may accept a specific turnover point within a wide temperature range. Common values are 25°C and 75°C, and he will expect to place the turnover point within +/-5°C to 10°C of that specified, this uncertainty arising from manufacturing tolerances.

In the case of NT-cut and +5°cut units, the manufacturer does not have complete freedom in positioning the parabola, and units may differ according to the individual manufacturer's choice of dimensions.

4.2 AT-CUT CURVE

The frequency-temperature (F-T) curve of the AT-cut quartz blank depends primarily upon the angle between the plane of the blank and the Z-axis of the quartz crystal (ZZ'angle). To a lesser extent the shape of F-T curve depends upon the ratio of the lateral dimensions of the blank to its thickness (D/t ratio). Figure 5 shows the F-T curves for AT-cuts at various ZZ' angles. In these curves the D/t ratio is assumed to be greater than about 25. If D/t is less than about 20 the shape of the F-T curve depends on the D/t ratio as well as the angle of orientation.

The orientation angle of a blank designed for a particular application depends upon the frequency, the dimensional ratio, the temperature range over which the unit is to operate, the permissible frequency excursion and the harmonic order (1, 3, 5, etc.). For example, a VHF unit designed to operate within a temperature range of -20° to +60° C with a frequency tolerance of +/-5 parts per million (ppm) would be cut at a ZZ′ angle of about 35° 22′. On the other hand, a unit designed to operate within the temperature range -55°C to + 90°C would be cut at an angle of about 35° 26′ and would have a frequency tolerance of about +/-20 ppm.

The customer should never attempt to specify the orientation or the dimensional ratio of the blank. His specification should state the temperature range within which the unit is to be operated and the limits of the permissible frequency excursion within the range. The frequency at a given temperature should not be specified unless the unit is intended for operation at that temperature. Typical examples are: units intended for use at room temperature or in thermostatically controlled ovens. If frequency "pulling" or "trimming" to frequency is anticipated, allowance must be made for this in setting the frequency tolerances.

Curves A, B, & C in Figure 6 show the effect of the F-T curve of drastic changes in the ZZ′ angle. Curve A shows the behavior of a blank cut at the optimum angle to maintain a frequency excursion no greater than +/-15 ppm within the temperature range -55 to +90 °C. Curves B and C show the effects of large changes on the ZZ′ angle. In curve B the frequency increase throughout the entire temperature range whereas in curve C it decreases over most of the range. The temperatures of the turning points of the F-T curves depend upon the ZZ′ angle. In curve A the turning point is between 65° and 70 °C. The temperature of the turning point may be raised or lowered but at the expense of greater frequency deviation over an extended frequency range.

4.3 SPECIFYING FREQUENCY TOLERANCE AND OPERATING TEMPERATURE RANGE

The temperature to which a crystal unit is subjected in an operating equipment may be considered higher than the ambient temperature due to internal heating; therefore, when specifying the temperature range within which the crystal unit must maintain a certain frequency tolerance, due allowance must be made for internal equipment heating.

The crystal unit manufacturer prefers a frequency specification of form the "+/- 100 ppm over the temperature range -40 °C to +70 °C" under stated load capacitance and drive level conditions. In the interests of customer and manufacturer alike, standard temperature ranges, frequency tolerance and input conditions should be used in all cases. Standard temperature ranges, frequency tolerances, etc., may be found in IEC Publications 122-1. It should be clearly understood that it is not practical to combine wide temperature ranges with very small frequency tolerances.

5. FREQUENCY STABILITY RELATED TO THE CONDITIONS OF USING THE CRYSTAL UNIT

5.1 FACTORS AFFECTING THE FREQUENCY STABILITY

In an oscillator whose frequency is determined principally by a quartz crystal unit, it must be understood that the circuit and conditions of operation have effects on the oscillation frequency.

Although a crystal unit is adjusted during manufacture to a nominal frequency, the conditions under which this frequency is actually obtained in a crystal oscillator must be carefully defined. It is the object of the following discussion to cover the more important considerations of this type. For convenience, some important points are listed here, referring to both the oscillator network and the crystal unit itself.

5.1.1 OSCILLATOR NETWORK

a) Load capacitance (Section 5.4)

b) Power and bias voltage supplies. Variations of these will generally affect the dynamic component of the load capacitance and the amplitude of oscillations, and hence the frequency (5.4 and 5.5).

c) Climatic and mechanical conditions. A true assessment of the effect of these is of great importance.

d) Aging of the circuit components.

5.1.2 CRYSTAL UNIT

a) Level of drive (5.5).

b) Operating temperature range.

c) Climatic and mechanical conditions. If these are more severe than those called for in the data sheets, the crystal manufacturer should be consulted.

d) Long term Frequency Drift. Generally speaking, only where very good frequency stability is required, should aging be of consequence. For detailed information, the manufacturer should be consulted.

5.2 TYPE OF OSCILLATORS

The many-varied configurations of crystal oscillators are the result of their many-varied applications. The simplest assemblies are found in the "quartz" oscillator used in watches and clocks, and the "clock" oscillators used in computers.

Somewhat more elaborate designs are used in radio receivers where they provide a reference frequency for channel selection synthesizers. The most critical applications are those in military satellite, and long range commercial systems where great stability is required. Temperature control, or compensation, is often required and both short-term and long-term frequency variations must be minimized.

The newest satellite navigation systems require the most stable oscillators for high accuracy in position determination.

For convenience, oscillators may be divided into two broad groups: positive reactance and series resonance oscillators.

5.2.1 POSITIVE REACTANCE OSCILLATORS

Figures 7 and 8 show the basic form of the positive reactance oscillator. The crystal is connected between the collector and the emitter of a transistor forming a tuned circuit with the capacitors connected to the base and collector terminals. The crystal produces a positive reactance at the frequency of oscillation equal in magnitude to the net negative reactance of the capacitors. Since a common-emitter amplifier produces a 180° phase inversion, the tuned circuit, as connected, produces an additional 180° resulting in positive feedback and oscillations.

The third capacitor, directly in series with the crystal, is the load capacitor, and is adjusted so that the net series capacitance (including the two base and emitter capacitors) equals the load capacitance specified for operation at the correct frequency.

A combination of bypassed and unbypassed emitter resistors are often used to stabilize the transistor's operating point. These also control the transconductance needed to insure stable operation. The minimum value required is

$$g_m = R_T/(X_1 * X_2)$$

where R_T represents the series resistance of the crystal plus the equivalent series resistance produced by base and load losses. X_1 and X_2 are the reactance of the base and collector capacitors respectively. The transconductance is usually adjusted to be at least twice the minimum value, and is dictated by the transistor's emitter current, and the value of the unbypassed emitter resistor.

Figure 7 represents a grounded-emitter circuit, while Figure 8 shows a grounded-collector version. The latter grounds one side of the crystal (which is often convenient at high frequencies) and also permits output to be taken either from the emitter, or from an impedance in series with the collector. This load impedance can be tuned to a harmonic of the crystal frequency, if required, but this should not be confused with overtone operation in which the crystal itself vibrates at an odd multiple of its fundamental mode. Both overtone operation and harmonic generation are possible in the same circuit.

When an overtone crystal is used, an additional inductor is often required in shunt with one of the tuning capacitors to inhibit operation at the fundamental mode.

An additional "trap" circuit will also be needed with an SC-cut crystal, to reject the normally undesired B-mode (appearing at a frequency approximately 10% above the C mode) and confine operation to the stable C-mode.

The upper frequency limit of positive reactance oscillators is controlled by the available transistor transconductance and the load capacitance. The latter dictates the minimum size of the base and collector capacitors and their reactance. At frequencies of 20 to 50 MHz, a load capacitance as low as 20 pfd, can be specified. This suggests that the equivalent series capacitance of the base and collector capacitors must be at least 20 pfd. Since capacitive reactance varies inversely with frequency, the product X_1X_2 in the gain equation becomes very small at higher frequencies. At frequencies above 50 MHz, where overtone units are employed, their higher resistances (see Figure 17), coupled with the reduced reactances, often demands a transconductance not easily realized. This situation can be avioded by using a different class of oscillators in which the crystal operates at series resonance.

5.2.2. SERIES RESONANCE OSCILLATORS

These are usually characterized by the inclusion of an L-C pair in the circuit. A "tank" (as this is often called) provides selectivity at the desired overtone frequency and thus eliminates the need for traps to prohibit operation at the fundamental, or at overtones lower than the desired mode. At VHF frequencies, the tank also increases the gain of the circuit.

Figure 9 shows a popular two-transistor circuit that can provide ample gain in the 50 to 200 MHz range. Q_2 operates as a grounded-base stage, offering a very low input impedance for the crystal current, while Q_1, connected as an emitter-follower, provides a low drive impedance for the resonator. Voltage gain is achieved via the tank circuit, whose high impedance, compared with the sum of the crystal resistance and dynamic emitter resistance, defines the gain. Since both stages are non-inverting, the amplifier provides the positive (regenerative) feedback required to sustain oscillation. The phase shift around the circuit is close to 0° at the resonant frequency of the tank and can be varied by +/-45° within the 3dB bandwidth of the tuned circuit. The circuit will only oscillate when the loop gain exceeds unity.

The operating frequency can be "pulled" to some degree by detuning the tank from the crystal frequency, but the reduction in gain that detuning produces will eventually stop the oscillation. When properly tuned, operation is at the series-resonant frequency of the crystal. A load capacitor can be used to increase frequency in the series-resonant oscillator just as it is used in positive reactance oscillator.

For high-frequency or high-impedance crystals, an inductor may be required across the unit to resonate with the shunt capacity C_o and prevent spurious oscillations.

A single transistor may also be used in a series-resonance oscillator, as shown in Figure 10. This is essentially the same as the circuit in Figure 9 with the emitter-follower replaced by a tap on the tank circuit. The tap is necessary to reduce the source impedance driving the crystal. Since the source is essentially the transformed load impedance, this circuit requires a heavy (low resistance) load to reduce the impedance.

In the absence of the emitter-follower, and as a result of the heavy load, this design requires a higher transistor gain (transconductance). This can be achieved with a high emitter current, and for VHF operation, a high F_T rating. Even then, a high resistance crystal, such as a fifth to ninth overtone unit, may not oscillate in this circuit.

The heavy loading can be beneficial in terms of reduced sideband noise. The higher power output of this oscillator can produce a higher signal-to-noise ratio.

While an increased load on a positive reactance oscillator increases R_T, the opposite is true of the two series-mode oscillators illustrated.

While positive-reactance oscillators also suffer from a low ratio of power output to crystal dissipation, the series-resonant oscillators provide a much higher power ratio. The cost of the improvement may be in increased circuit complexity due to the L-C circuit, but when overtone units are used, particularly the SC-cut, additional inductors are needed in any case.

5.2.3 CRYSTAL Q AND ITS IMPLICATIONS

It has been stated that a crystal resonator has an equivalent circuit (in the region of resonance) consisting of an inductance L_i and capacitance C_i, in series with a resistance R_i, all shunted by the electrode capacitance C_o. As with a conventional L-C tuned circuit, the resonator's performance can be given a "quality rating" defined as Q where

$$Q=1/wC_iR_i = wL_i/R_i$$

since at series resonance, $W^2 L_iC_i = 0$.

The Q-factor can also be defined in terms of phase change versus frequency change; thus,

$$Q=d\phi/2df/f=d\phi/2dw/w$$

The stability of a crystal oscillator can then be defined in terms of the change in frequency, df, resulting from changes in phase, $d\phi$, occurring in the sustaining amplifier's circuit. The equation for Q can thus be written

$$df/f=d\phi/2Q$$

which indicated that the frequency stability is a function of resonator Q.

All of the circuits discussed above reduce the crystal's Q by a factor equal to

$$Q_L = Q_i \times R_i / R_T$$

where Q_L is the loaded Q, R_i is the intrinsic (motional) resistance of the crystal and R_T is the sum of R_i and the ESR of the circuit losses and resistance.

A reduced Q then, makes the frequency of oscillation more susceptible to changes in phase, whether in the transistor or in the passive components. Phase changes due to thermal noise, 1/f (flicker) noise, and the excess noise produced by semiconductor charge-carrier variations are also converted to frequency jitter.

Modern resonators exhibit unloaded Q factors ranging from 2×10^6 at 5 and 10 MHz, to 5×10^4 at 100 MHz and above.

5.2.4 SERIES-MODE OSCILLATORS USING THE MEACHAM BRIDGE

A circuit that offers increased resistance to phase changes in the feedback loop, uses a bridge circuit operating slightly off balance. The Meacham Bridge is a four-arm bridge in which two arms provide a reference voltages for the third and fourth arms which comprise a resistor and the resonator. The output of the bridge is the voltage between the center points of the two pairs of arms.

It is the property of a resonant bridge circuit to produce a higher phase change with frequency, than the resonator alone produces. As the bridge is adjusted closer to the balance point the phase slope increases, approaching infinity at the balance point. In the practical circuits described below, the bridge must be operated off balance, to a degree determined by the available amplifier gain.

This property is utilized in bridge oscillators to increase the effective phase slope of the resonator and thus reduce frequency jitter and noise, around the operating frequency.

Figure 11 illustrates one form of bridge oscillator in which a tuned circuit L_1, C_1, C_2 provides two out-of-phase voltages and in which the bridge is completed with the crystal and resistor R_1. The degree of unbalance, and hence the phase (or Q-) multiplication, depends on the gain of the sustaining amplifier since the overall gain must be greater than one. Hence, an unbalance of 5% requires an amplifier gain greater than 20.

A slightly more complex circuit is shown in Figure 12, that differs from the single-transistor version in that it uses a differential amplifier to provide the out-of-phase voltage. The available output power is greater and has reduced even-order harmonic content. It is suitable for operation to 100 MHz.

The necessary condition for oscillation can best be expressed in terms of positive and negative feedback ratios, Bp and Bn, which can be combined in the basic expression used for gain of an amplifier with voltage feedback; e.g. $A = A_o/(1-A_o(Bp - Bn))$
under these conditions the circuit will oscillate when the denominator reaches zero, and the gain becomes infinite. This occurs when

$$A_o(Bp - Bn) = 1$$

Referring to Figure 12, the positive feedback is produced by the voltage divider comprised of C_2 and C_3 while negative feedback is due to the divider comprising R_1 and the crystal resistance R_i This leads to the definition for Bp and Bn.

$$Bp = \frac{C_2}{C_2 + C_3} \quad \text{and} \quad Bn = \frac{R_i}{R_L + R_i}$$

The frequency at which the phase shift in the system is zero, defines the frequency of oscillation. This can be modified by the use of loading capacitor C_L in the same manner as described previously, but also by C_x which has the opposite effect of reducing the operating frequency.

As in other series-mode oscillators, the tank circuit restricts operation freqiuencies to within its bandwidth, and thus prevents operation on undesired overtones, or on the B-mode when using SC-cut crystals.

Bridge oscillators, unlike the previously discussed circuits, operate better with high resistance crystals and are well suited to driving high overtone modes. The circuit in Figure 11. can be used with overtone crystals up to 500 MHz.

5.2.5 INTEGRATED CIRCUIT CRYSTAL OSCILLATORS

Some of the circuits discussed earlier can be modified to work with IC's. This is often necessary, or at least convenient, with digital instruments and computers.

Figure 13 illustrates how the common IC inverter can be used in a positive reactance oscillator. (These are often built-in to microprocessor, divider and phase-locked loop (PPL) chips for convenience.) The inverter can be transformed into a linear amplifier by connecting a high-value resistor between input and output terminals. This technique is best applied to CMOS chips, whose input impedance is extremely high, so that no current is drawn through the bias resistor. Both the D.C. input and output voltages are held at the midpoint of the supply by the feedback, and the linear gain can be quite high, depending on how many stages are in the inverter. An unbuffered inverter consists of a single stage with a voltage gain ranging from ten to one hundred, while buffered units usually have three stages (to achieve inversion) with gains in excess of one thousand. The unbuffered units, especially in high-speed CMOS, have upper frequency limits in excess of 30 MHz. Buffered units, having higher propagation delays, are useful to 10 MHz.

The current drawn by these inverters can be very high when not oscillating since both of the two series FET's that constitute the inverter are drawing current. When used as oscillators, the current is reduced to a minimum at saturation; i.e., with only one FET on at a time. The average current will then be proportional to the operating frequency and the transit time ratings.

Since the resonator, and its associated capacitors, as shown in Figure 13, constitute a narrow bandpass, positive reactance circuit, the inclusion of resistor R_1 allows the square wave output from the inverter to be converter into a since wave at the capacitor's terminals. R_1 also controls the loop gain and should be adjusted to as high a value as possible, consistent with power consumption and frequency stability.

The circuit of Figure 14 is much more stable due to its bridge configuration. It requires an amplifier with a differential input. These are available in bipolar IC packages intended for RF and video amplifier applications. The series-resonant mode of operation was described in section 5.2.4 where an L-C tank was used to provide the in-phase and out-of-phase voltages required for arms 1 and 2 of the bridge. The simplified circuit shown here is aperiodic since it uses resistors to control both the positive and negative feedback voltages, and will operate in the lowest resistance mode of the resonator, provided it falls within the frequency limit of the amplifier. Tuning can be provided for overtone selection by using an L-C tank between the differential input terminals of the amplifier.

5.3 LEVEL CONTROL

In applications requiring the highest frequency stability it is necessary that some means of level control be incorporated into the oscillator circuit in addition to temperature control. Holding the crystal current to a stable value below the saturation level of the amplifier also reduces the signal distortion amplifier that causes cross-modulation products and raises phase-noise levels in the sidebands. Excessively low drive levels on the other hand reduce signal-to-thermal noise ratio and so an optimum level exists.

A simple form of of amplitude limiting often employed, consists of a pair of diodes back-to-back, as shown in the dotted lines in Figures 10, 11, and 12. In the first example, the diodes increase the load on the tuned circuit at signal levels exceeding the turn-on voltage of the diodes but below the saturation level of the amplifier. This helps stabilize the output level but still produces distortion of the output signal.

Figures 11 and 12 show how the diodes can be used in a bridge oscillator to increase the negative feedback rather than reduce amplifier gain.

More elaborate systems that introduce negligible distortion are shown in Figures 15 and 16. The amplified output of the oscillator is rectified and filtered to produce a control voltage which, will in turn, reduce the gain of the sustaining amplifier to a stable level. The output of the oscillator is then just sufficient to supply the necessary control levels. The higher the gain of the buffer amplifier, the lower the oscillator (and crystal) voltage and current levels.

Figure 16 uses a junction FET as a variable feedback resistance in a bridge oscillator to control signal level without reduction of sustaining amplifier gain. The bridge operates closer to the balance point, with an attendant increase in circuit stability.

The rectifier circuits used in these examples are voltage-doubler designs and the use of Schottkey diodes are recommended for maximum conversion gain.

5.4 LOAD CAPACITANCE

In positive-reactance oscillators, the crystal is designed to operate as an inductive impedance, being connected to an amplifier which appears capacitive at the crystal socket. It is this load capacitance which is the principal external influence in determining the operating frequency of the oscillator; thus, the influence of mechanical and climatic conditions on the value of the load capacitance should be kept as small as possible.

Typical rates of change of frequency with change of load capacitance are given in Table 3. These figures also apply when the frequency is intentionally pulled (Section 6.3).

TABLE 3

Frequency variation df/f in parts per million per Pf change in normal load capacitance						
	Mean 20 pF		Mean 30 pF		Mean 50 pF	
	f min	f min	f min	f min	f min	f min
A fundamental	10	20	4	12	2	5
B overtone(3)	1.5	2.5	1	1.5	0.3	0.6
B	6	14	3	8	1	3
C	4	11	2	6	1	3
D	5	16	2.5	9	1	4
G	12	13	6	7.5	2.5	3.5
E	-20	40	12	30	6	15
SC-cut						

Further, because crystal units are designed to operate with a definite value of load capacitance, steps must be taken to insure that the capacitance is in fact present to the crystal. The effects in stray capacitance and dynamic capacitance; vis., those introduced by the transistor, operating as an amplifier must be carefully evaluated.

In order to minimize correlation problems, the value of C_0 should always be specified with appropriate limits. Frequency at which C_0 is to be measured should also be specified if the unit is designed to operate in the 100 MHz range or higher.

Standard values of load capacitance for fundamental crystals are given in Section One of IEC Publication 122-1. For fundamental crystals, 30 pF is often preferred as giving the best compromise between high output and good frequency stability.

Overtone crystal units are usually operated at series resonance, but in those cases where a load capacitance must be used, reference should be made to IEC Publication 122-1 for the standard values. Figure 18 gives a general impression of the variation of the series resonance resistance that may be encountered.

5.5 LEVEL OF DRIVE

The level of drive imposed by an oscillator is usually specified in terms of the power dissipated in the crystal unit. Ideally, the crystal oscillator should be regarded as a source of power.

Rated levels of drive are shown on the data sheets for various types and frequencies of crystal units, and it will be seen that they are never greater than a few milliwatts. Exceeding the specified values may lead to permanent damage to the crystal units, and will certainly degrade the frequency stability. Further, since overdrive causes the frequency of the crystal to shift, either permanently or for the time the drive is imposed, it is quite possible that the shift will be greater than the allowable frequency tolerance; thus, it is seen that the equipment designer should take that variations between components, supply voltage variations, etc., do not result in rated drive levels being exceeded. On the other hand, it may be undersirable in some cases to allow the drive level to fall much below the rated value; this is not so much in the interests of getting higher stability, but to insure that the frequency of oscillation shall be within the required tolerance. Since the manufacturer adjusts the frequencies of crystal units at the rated level of drive, it is desirable that the user should operate the crystal unit under similar conditions.

5.6 LEVEL CONTROL

In applications requiring good frequency stability, it may be necessary to incorporate some means for level control into the oscillator circuit. Amplitude limiting by means of diode clamps, as illustrated by the circuits in Figures 10, 11 and 12 provides a very convenient method. These circuits operate the crystal network at series resonance, facilitating resistance substitution alignment techniques, and uses an electrical network to provide the required loop phase, as well as to reduce the harmonic content at the output. Since the electrical network is of the bandpass type, the circuit may be used with both fundamental and overtone mode crystal units over the frequency range from below 100 kHz to 100 MHz or higher.

Other methods used in high-precision circuits to obtain very constant drive level controls are shown schematically in Figures 15 and 16. Here, an electronic delayed gain control loop is provided, so that when the oscillator reaches a prescribed level of operation, the AGC circuit is energized and reduces the bias of the oscillator stage until unity loop gain conditions are established, and stable, low level operation is assured. Such oscillator circuits can be made to operate at very low levels as essentially linear amplifier stages.

6. SPECIAL REQUIREMENTS

The standardization of specifications and operating conditions for crystal units is intended to make it possible to select readily available standard units to cover most requirements, and every effort should be made to use such units. In certain cases, standard items will be adequate for use under conditions other than those specified for crystal unit, but since it is possible that the crystal manufacturer can alter considerably the design of a crystal unit while keeping it within the standard specification, such alterations may well render the new unit unusable except for these non-standard applications. It must be stressed; therefore, that it is essential for the user to inform the manufacturer of his particular applications when they are non-standard.

The following may be taken as examples of special requirements.

6.1 TOTAL FREQUENCY VARIATION OVER THE OPERATING TEMPERATURE RANGE

The definition of the limits of this variation may be necessary to permit trimming for greater accuracy of frequency adjustment. It can be used to eliminate that part of the frequency error resulting from manufacturing adjustment, load capacitance deviations, and any subsequent frequency drift due to aging. This should only be sought where the frequency tolerance required is closer than any offered in the standard patterns for the requisite temperature range, and where an adequate frequency standard will be available to monitor the adjustment.

6.2 FREQUENCY VARIATION OUTSIDE THE OPERATING TEMPERATURE RANGE

The definition of the limits of this variation may be necessary in the case if crystal units to be operated in temperature-controlled ovens to allow for adjustment.

6.3 FREQUENCY PULLING

Since the equivalent impedance of a crystal unit is a function of the frequency, it is possible, by causing this impedance to change, to alter the operating frequency. This is most easily effected in an oscillator by putting a variable reactance either in series or in parallel with the crystal, the actual choice being decided by the nature of the oscillator circuit used. For example, in the oscillator of Figure 7, the load capacitance could be changed by putting a variable capacitor across the crystal socket, where the frequency would change according to the following relation:

$$\frac{f_1 - f_2}{f_1} = \frac{C_i}{2} * \frac{C_{L2} - C_{L1}}{(C_o + C_{L1})(C_o + C_{L2})}$$

Here f_1 and f_2 are the oscillator frequencies at load capacitances C_{L1} and C_{L2}.

C_i and C_o are the motional and parallel capacitances of the crystal unit. It is seen that the frequency shift $f_1 - f_2$ depends upon C_i and C_o, which in turn depends upon the crystal unit design. Consequently, where consistent frequency adjustment is important, the crystal parameters must be agreed upon the the manufacturer, for they may vary widely from one manufacturer to another, even for crystal units of the same frequency and in the same holder. Where necessary, the manufacturer can advise on the values of C_1 and C_o for a given frequency and cut. (See the table in Section 5.4 for typical frequency shifts for various crystal types.)

There are limitations to the amount of frequency pulling available, for if the load capacitance increases too much, the activity of the crystal unit will fall below the value required to maintain oscillation. The load capacitance is made very small the effects of stray capacitance may affect the overall frequency stability or the drive level may become excessive.

Similar remarks to those above may be applied to series resonance oscillators, except that in this case the variable reactance is usually connected in series with the crystal unit.

Another point on the series oscillator is that its frequency may be adjusted by detuning the normal tuned circuit from its optimum setting, but this is not advisable for it results in a reduced output and may result in oscillation at unwanted mode if the circuit is detuned by a large amount.

6.4 SERIES RESONANCE OPERATION OF FUNDAMENTAL CRYSTAL UNITS

Occasionally, it may prove necessary to use fundamental crystal units at series resonance within the band 1-25 MHz. Maximum levels of drive will be the same as for a crystal unit of the same type adjusted for parallel resonance.

Many series-resonance circuits give sensibly constant crystal current irrespective of variations of ERS, at a given frequency. In these cases, it may prove more convenient to specify the operating level on a current basis, but when this involves an excessive drive level in terms of power, this may result in a necessary relaxation in other operating conditions such as frequency tolerance. Any variation of crystal current with frequency should be taken into account when drawing up the specification in collaboration with the manufacturer.

6.5 CLIMATIC AND MECHANICAL EXTREMES

When crystal units may be subjected to mechanical and climatic conditions more severe than those laid down in the specification, the manufacturer should be consulted.

6.6 MARKING

When additional marking is required other than that specified in the data sheet, the manufacturer should be consulted.

7. MEASURING METHODS AND TEST CONDITIONS

The measurements and test will normally be those recommended in the relevant specifications.

8. TECHNICAL DATA TO ACCOMPANY ORDER FORM

Where the requirements can be met by a standard item, it will sufficient to specify the frequency(ies) and the data sheet for the item(s).

When the requirements cannot wholly be met by an existing data sheet, it should quoted together with known differences; e.g.:

Nominal frequency(ies) . . .kHz

Data sheet number . . .

Except that . . .

Frequency tolerance +/-30 X 10^6

Operating temperature range +10°C to +60°C

In the very unusual case where the differences are such that it is not reasonable to quote an existing data sheet, a new one should be prepared in a similar form to that already used for standard data sheets.

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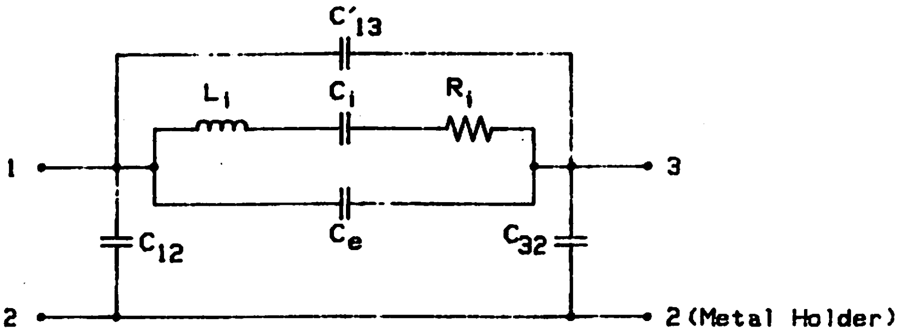
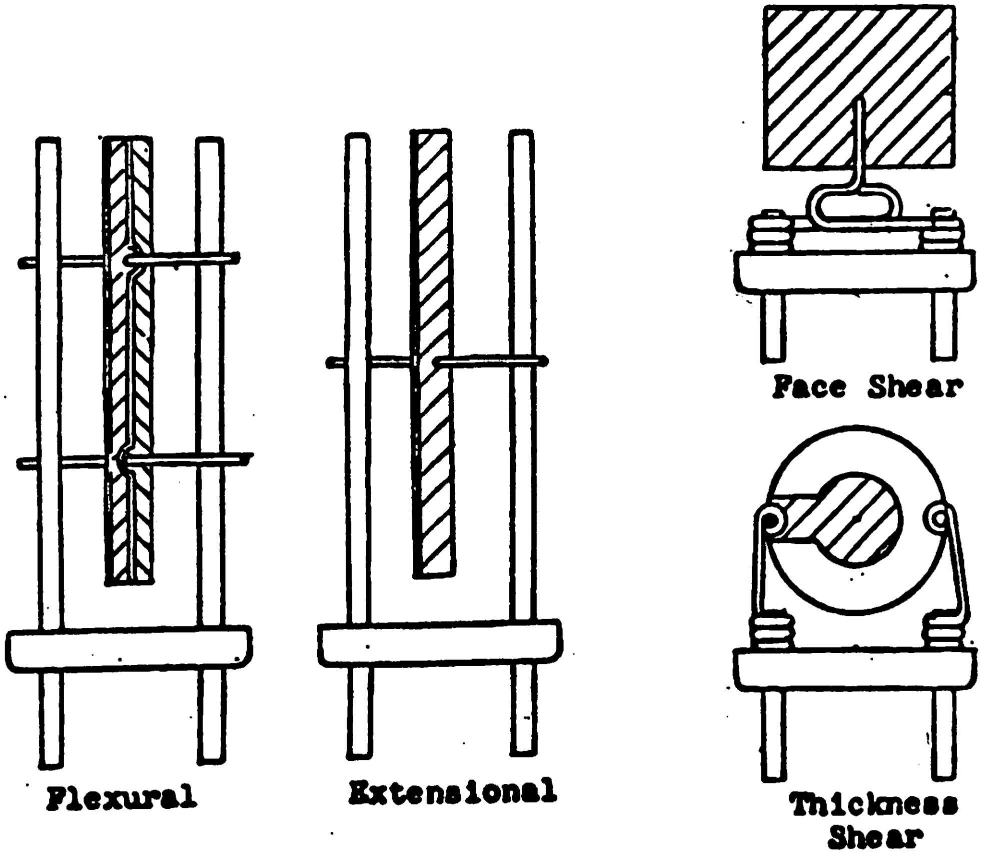


EQUIVALENT CIRCUIT

FIGURE 1



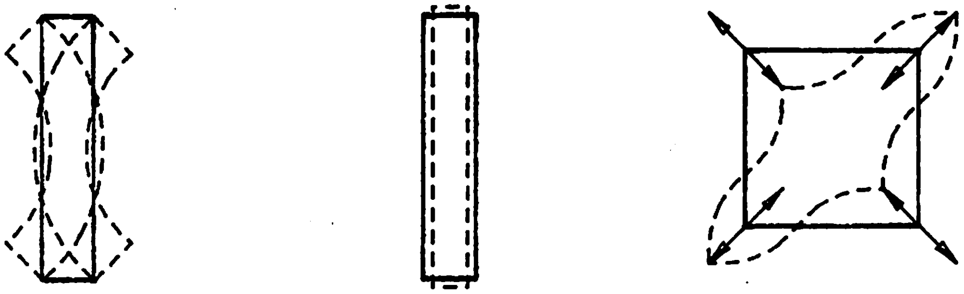
Flexural

Extensional

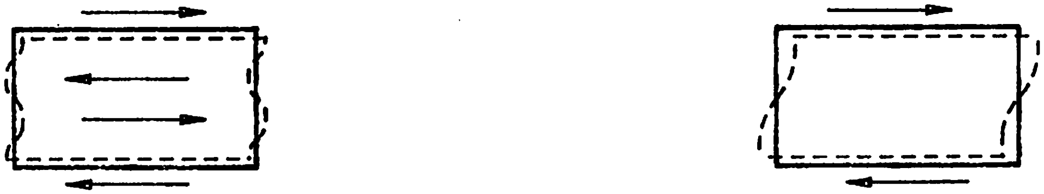
Face Shear

Thickness Shear

Fig. 2 Methods of Mounting, in Simplified Form



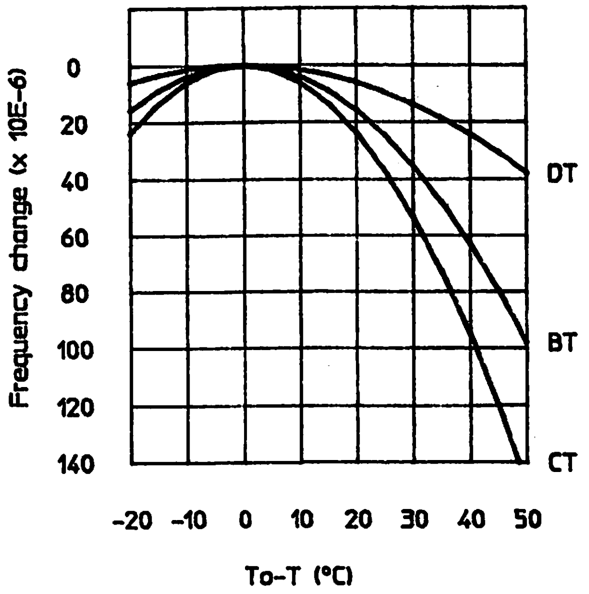
FLEXURAL EXTENSIONAL FACE SHEAR

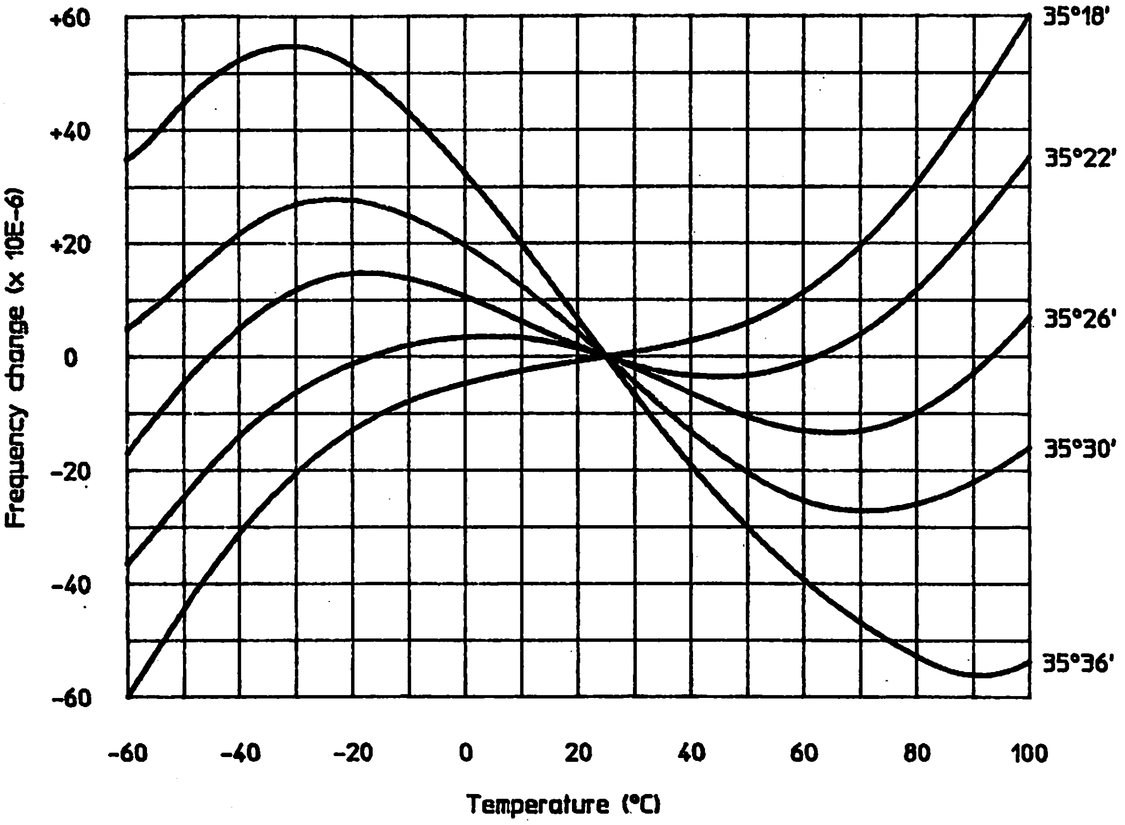


THIRD OVERTONE FUNDAMENTAL

THICKNESS SHEAR

MODES OF VIBRATION
FIGURE 3





FREQ.-TEMP. VS ZZ' ORIENTATION ANGLE
FOR VHF AT-CUT CRYSTALS

FIGURE 5

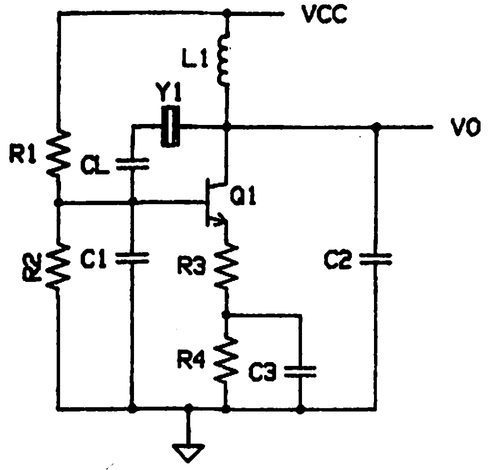


FIGURE 7

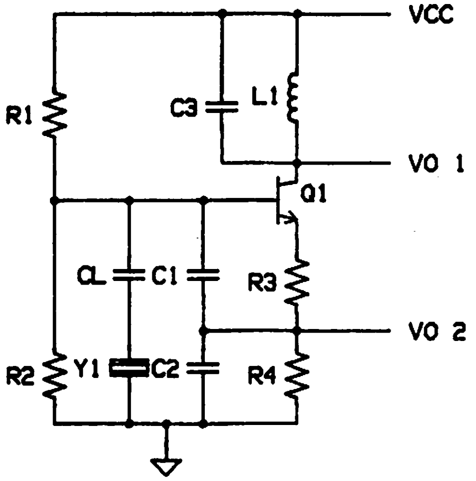


FIGURE 8

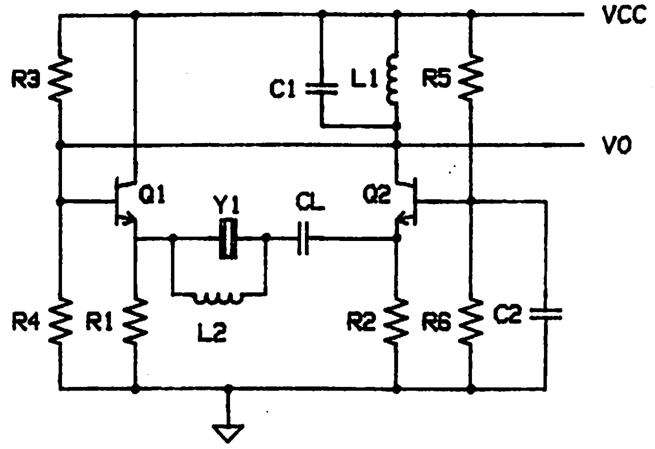


FIGURE 9

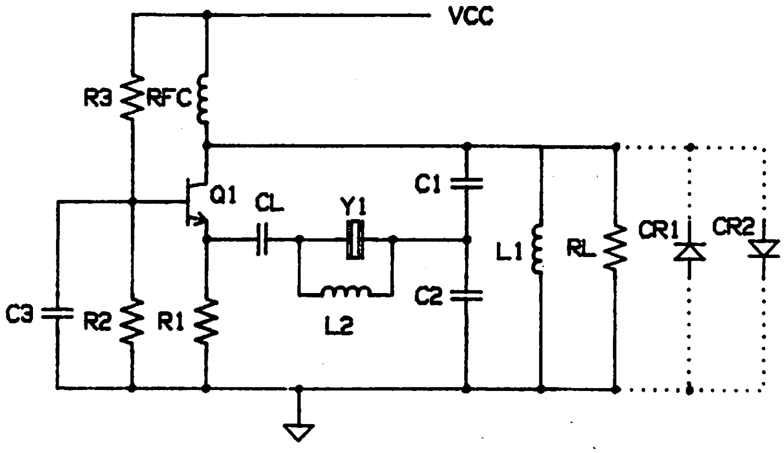


FIGURE 10

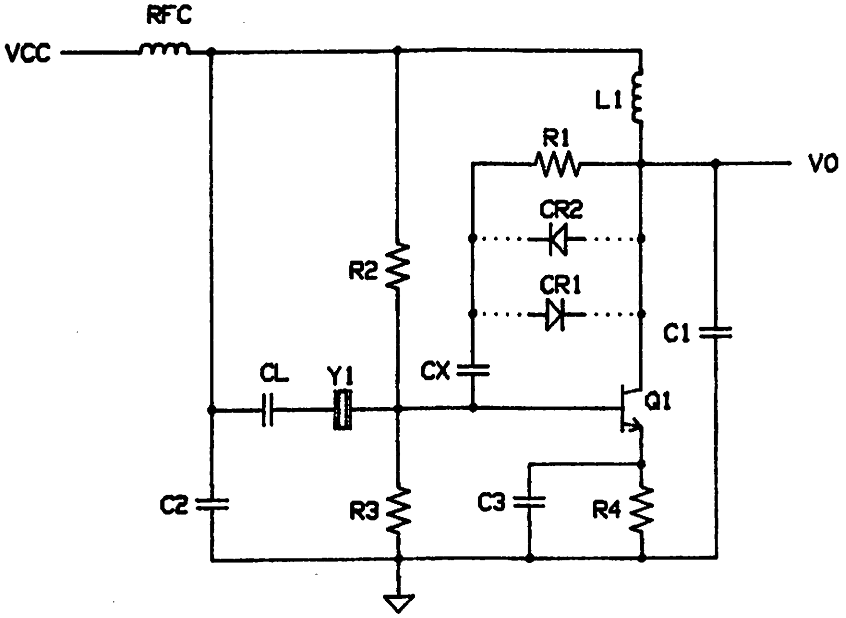


FIGURE 11

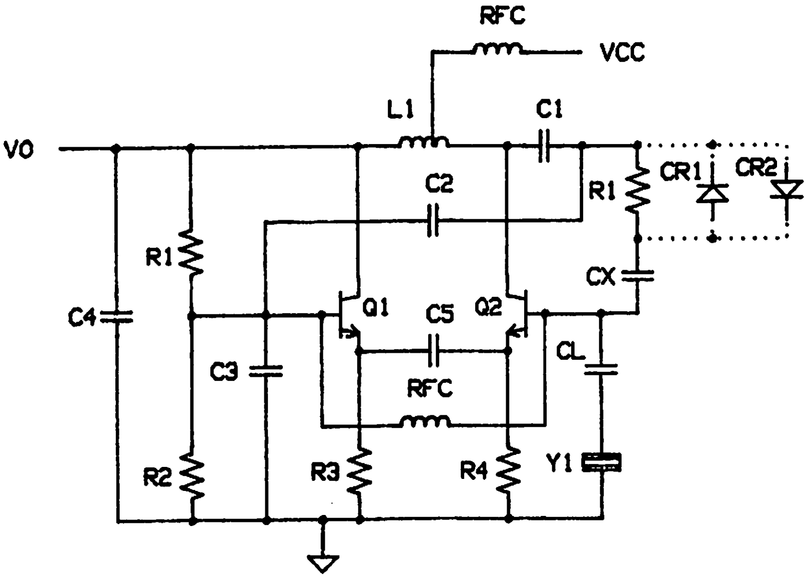


FIGURE 12

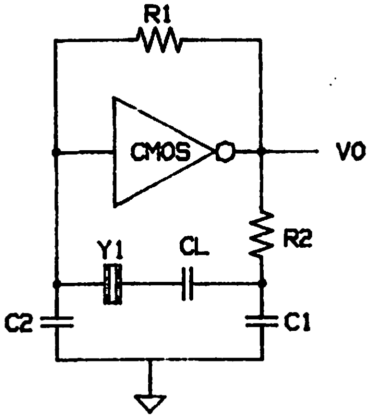


FIGURE 13

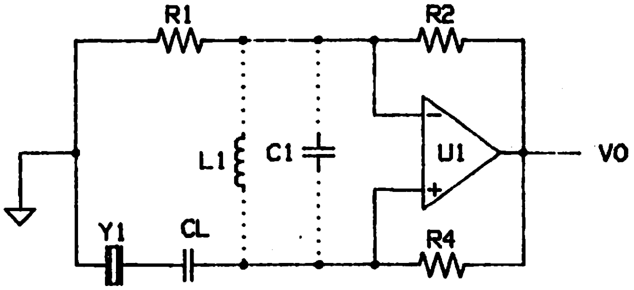


FIGURE 14

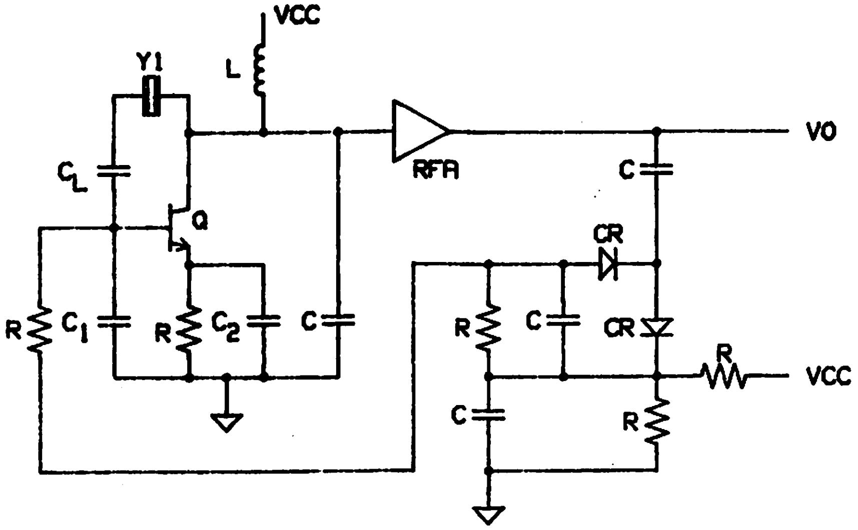


FIGURE 15

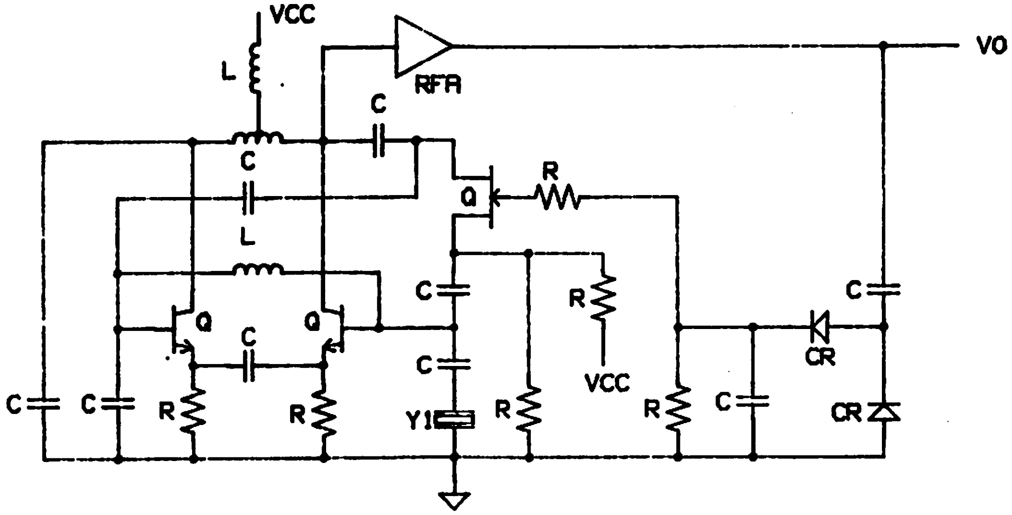
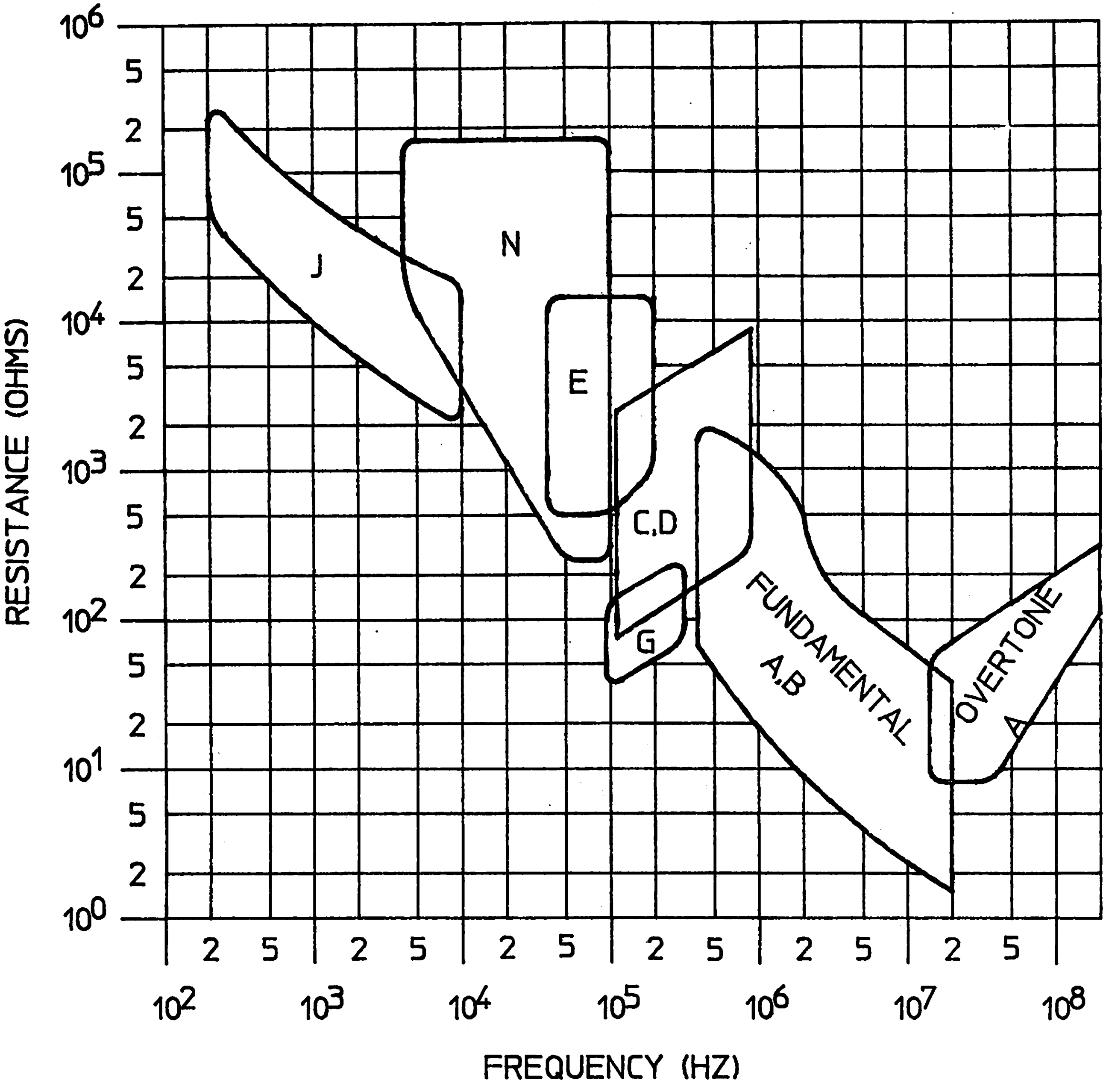


FIGURE 16



SERIES RESONANCE RESISTANCE
AS A FUNCTION OF FREQUENCY
FOR CRYSTAL RESONATORS

FIGURE 17


ELECTRONIC INDUSTRIES ASSOCIATION
EIA
EST. 1924