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Guide for the Use of Quartz Crystal Units for Frequency Control

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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



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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 compiled 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_0 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_0 must be determined by considering C_0 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_0 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_1 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_1 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_1 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_0/C_1 . 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_1 at

certain temperatures; the unit may even fail to operate. The increase of R_i 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 desirable 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



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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

"Vibra tor" Desig- nation :	Usual Description :	Mode of Vibration :	Usual Frequency Range :	Approx. C_0/C_1
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.)		
	IT or SC	Thickness	15000- 150000 kHz	
		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_0/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_0/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-shear 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