THE PIEZOELECTRIC QUARTZ RESONATOR

Karl S. Van Dyke*

Contents

I. The Contributing Properties of Quartz

A. *Highly Perfect Elastic Properties*

The excellence of quartz for use in frequency control is expressed in the large numerical values of Q in quartz resonators, which the use of this

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* Director of Research, Long Branch Signal Laboratory, U. S. Army Signal Corps. Also, Professor of Physics, Wesleyan University, on leave of absence.

highly elastic material makes possible. Q is a number used in acoustics and in electrical engineering in listing, for vibrating systems, their relative efficiencies of transfer of energy back and forth between strain and motion, or from potential to kinetic energy. This efficiency is limited for a given material by the viscous dissipation of energy in the elastic straining process, and is correspondingly limited in the case of oscillatory electric circuits by the loss of energy in electrical resistance. One form of definition is that Q is the ratio of energy stored to energy dissipated, per cycle.

Among elastic substances, quartz has, to the greatest degree known, this property of enabling high Q to be attained. This is equivalent to saying that a bell made of quartz, mounted in such a way that in "sounding" it does not transmit vibrations to its supports, and contained in an evacuated housing so that it radiates no sound, would ring longer, once struck, than if made of any other material. The values of Q measured for cylindrical rings of quartz vibrating at supersonic frequencies have run as high as several million, indicating specifically that the quartz ring, once started in its resonant vibrations, but without being further driven, completes several million vibrations during the time of the decay of its vibration to a value about one-third of the original amplitude (to a fraction equal to the reciprocal of the base of the natural logarithms instead of $\frac{1}{3}$, to be exact).

Not only do quartz resonators have the highest Q's known but they exceed those for the best of other measured elastic substances a hundredfold. Furthermore, the Q's of the best resonant electrical wire-circuits are less than a hundredth of those attainable in quartz resonators. Quartz crystals used in communication equipment commonly have Q's in the hundred thousands, the values depending upon the mountings, cleanliness, and precision of manufacture.

It is, in the last analysis, the degree of long-ringing power which determines the ability of any type of element to attain precision in controlling the frequency of an oscillating device. Looked at another way, Q is the measure of frequency-selectivity; that is, of the ability of a device to discriminate between frequencies nearly alike. A quartz element can be made a hundred times more sharply frequency-selective than elements of any other known material and is thus to the same degree more effective than any other device in holding the frequency of an oscillatory system, such as a radio oscillator, to the frequency preferred by the controlling element, in this case the quartz. The property of quartz under discussion is sometimes stated in terms of inverse properties such as the viscosity of the material and the damping of the vibration. Quartz has very low values for these.

B. *The Piezoelectric Property*

It is axiomatic that only materials which have electric properties can serve as circuit elements. Glass and mica are used as the dielectrics of electrical condensers owing to their characteristic electrical response to electric fields. Except for negligibly small mechanical deformations, known under the term electrostriction, the strains which simple dielectrics experience in an electric field are purely electrical. Quartz, also, has dielectric properties. But in addition, quartz in its crystalline form is piezoelectric, and experiences a second and more significant mechanical deformation under the influence of an electric field. This mechanical strain at any point in the quartz may be extensional (or compressional) and/or of a shear type depending upon the direction of the applied electric field in relation to the crystallographic axes.

The piezoelectric effect is a reversible one so that conversely when crystalline quartz is strained mechanically, there is called into being within the quartz an electrical polarization of the material which tends to set up charges on certain surfaces of the crystal or upon any nearby electrodes. It is its piezoelectric property which underlies the use of crystalline quartz in resonant circuit elements and is responsible for its affecting the circuit in another way than through its dielectric effect.

A piezoelectric element is thus more than a simple electrical condenser. The basic circuit effect is that in addition to currents through the quartz which are characteristic of its behavior as a dielectric, currents also flow through it as it deforms. The magnitude of this additional current is greater as the rate of deforming is more rapid, and the current reverses in direction as the rate of strain reverses. Thus, when any piezoelectric circuit element is in vibration, alternating currents flow through the quartz and through associated circuit elements as if there were an alternating electric generator hidden within the quartz and running in step with the changing of strain of the vibration, a generator which produces circuit reactions quite analogous to the more familiar counter e.m.f.'s of self-induction and other circuit properties. Although picturing the vibrating piece of quartz as an electric generator is particularly convenient when the energy which drives the vibration comes from outside of the circuit, as from sound waves impinging upon the quartz, its portrayal as a purely reactive circuit element such as a resonator is more appropriate for its radio uses.

C. *The Piezoelectric Resonator*

The flow of electric currents in circuits depends wholly upon voltages and such circuit elements as resistance, capacitance, and inductance. Following out of the fact that the deforming of a quartz crystal is directly related to the flow of current in its part of the circuit, the effect on the current in the circuit is as if the quartz element were some fixed combination of conventional circuit elements. The magnitudes in the combination can be expressed in conventional measures, but they represent values which are so far out of the ordinary that the equivalent circuit elements which would duplicate the circuit reaction are far beyond the ability of electrical engineers to construct physically. Piezoelectric currents of quartz elements are inherently small but are multiplied by the phenomenon of resonance. Yet even at resonance they are limited by the fracture strain of the material.

In one sense, the most significant fact regarding the equivalent circuit elements for a quartz mechanical resonator is that they constitute a tuned circuit, in this case an electrical resonator, and that this tuned circuit has a value for Q, to indicate its electrical frequency-selectivity, which is the same as that which characterizes the mechanical vibrating device. As stated, this value may be a hundred or more times as large as for the best wire-made electric circuits that could be built.

It is in the nature of the interaction of resonator and circuit that the more loosely the resonator may be coupled to the circuit and still affect it, the more rigidly is the resonator's own uniqueness maintained as a frequency of reference unaffected by the circuit. Resonator reaction on the circuit may remain effective through a more extreme loosening of the coupling the higher the Q of the resonator.

When quartz is used as a resonator in a radio circuit, no direct use is made of the mechanical vibration which is driven piezoelectrically by the circuit, or of the fact that the storage of the energy of vibration is accomplished mechanically rather than electrically, but only of the electrical reaction of the mechanical vibration back on the driving circuit, again through the piezoelectric effect. In other applications, piezoelectric elements serve to couple an electrical and a mechanical medium. Thus, in a loud-speaker or in a supersonic generator, piezoelectric crystals drive sound waves in an acoustic medium through the mechanical strains and motions which are set up in the piezoelectric material by an applied electric field. Conversely, piezoelectric crystals serve as microphones, in which sound waves in the fluid medium are themselves responsible for producing mechanical strains in the crystal, which in turn are inherently accompanied by voltages set up piezoelectrically. These latter drive currents in the rest of the circuit of which the piezoelectric element is a part. In these applications, the crystal's function is as a transducer, so-called in communication engineering literature, to lead vibrational energy from one medium to the other, as from the electric circuit to the acoustic medium, or vice versa. In contrast to the resonator application, which is of principal concern in radio and telephone communication, and in control of frequency, it is not usually important that the crystal element which is used as a transducer have a high Q. One crystal used in transducer applications is Rochelle salt, which has elastic properties very inferior to those of quartz. It has, however, much larger piezoelectric properties; larger strain results from an equal field, and greater current through the crystal accompanies an equal rate of strain.

D. *Other Factors in the Common Circuit Use of Quartz*

The mechanical resonance frequencies in a piece of quartz depend upon its size. As in other systems of stationary waves, the period of the vibration is the time required for the mechanical wave in the material to complete the round-trip between opposing boundaries of the system. The speed of elastic-wave travel in quartz is such that round-trips in pieces whose frequency-determining dimensions lie in the range between a fraction of a millimeter and a few inches, require lengths of time which correspond to the intervals between successive alternations of currents of the frequencies used in radio. Thus, fortunately, quartz resonators which are tuned to radio frequencies have convenient dimensions. Small crystals are associated with high frequencies and the whole gamut of frequencies for which quartz is used runs from a couple of kilocycles per second (kc/sec), which is a voice frequency rather than a radio frequency, to a hundred or more megacycles per second (mc/sec). The shorter the dimension of a crystal along which the standing elastic wave is set up, the higher is the radio frequency to which the crystal is resonant, although the scheme is sometimes adopted of getting resonance at higher frequencies by letting the standing wave system be a number of half waves long instead of one.

No small factor in the importance of quartz crystals as standards of frequency in radio communication is the excellence of its other properties in addition to the elasticity already referred to; notably, its chemical stability and permanence under a wide range of conditions, its low solubility, and its mechanical hardness. Again, some of its elastic compliances, have positive temperature coefficients while others have negative, and this offers great possibilities for balancing compensating temperature effects on frequency against one another. Highly important to its recent extensive military application has been the fact that quartz was available, and the further fact that there has existed wide knowledge of its detailed properties following years of intensive investigation of its resonator behavior.

II. THE MECHANISM OF CIRCUIT INFLUENCE BY QUARTZ

A. *The Piezoelectric Strain-Current Relation*

It has been pointed out that electric current flows through the quartz during the changing of its state of strain, that the quartz unit may be regarded as a circuit element, and that as such it has both dielectric and resonator properties. If it were possible to so firmly clamp the piece of quartz that the circuit voltages could produce no mechanical strains, the crystal would serve merely as an ordinary condenser. The piezoelectric currents are over and above those due to this condenser element of clamped quartz, and are properly regarded as motional currents from their association with the motion of the quartz. Analogous motional currents and motional impedance properties are familiar in the treatment of loudspeakers.

In its electric circuit representation, the effect of freedom of vibrational motion of the quartz shows up as a second branch of the circuit, bypassing the condenser. This parallel branch is fictional rather than physical, but the laws governing the flow of current in the rest of the circuit include the reactive effects of such an equivalent circuit having a characteristic motional impedance. The piezoelectric property of the quartz may be thought of as serving a sort of mirror-like function, whereby the current flowing in the circuit leading up to the quartz sees, as opposition or impedance to its flow, an electrical image of the mechanical opposition which the quartz offers to the forces which the applied voltage has set up to drive it. Stated again, the piezoelectric effect offers a translating formula whereby mechanical properties develop electrical properties in the circuit in proportion to their own magnitudes. It has long been a custom to think of alternating current circuit behavior in terms of the vibration of mechanical analogies. In this case, however, we have more than an analogous behavior; the mass, stiffness and viscosity of the quartz actually appear as parameters in the electric circuit multiplied by appropriate coupling factors; similarly, these coupling factors interrelate electromotive force and mechanomotive force, electric current and strain velocity. The quantitative basis of these associated effects is in each case a piezoelectric constant of the quartz modified by specific dimensions, by the type of strain involved in the vibration, and by the direction of the electric field in the quartz to which the external circuit is made susceptible.

The magnitude of the current in this parallel motional branch, in other words the piezoelectric current, is usually negligibly small compared to the dielectric current of the condenser except when the frequency of the driving voltage is close to a resonance response frequency of the piece of quartz. At such a frequency the extraordinarily large value of the Q multiplies or enhances the current in the imaginary piezoelectric branch by a factor of the same order of magnitude as the Q. That is, the effect of high Q is to reduce greatly the magnitude of the electrical impedance of the piezoelectric branch at resonance. With Q's of the order of 100,000, the piezoelectric responses, both the current and the mechanical strains, usually become large enough at resonance to overshadow completely the dielectric effect. It is the mechanical resonance effect alone, this multiplication by large Q, which brings the otherwise exceedingly feeble piezoelectric currents into usefulness in the radio field.

B. *The Several Circuit Uses of a Crystal Resonator*

Quartz crystals are sometimes confusingly spoken of as being either oscillators, calibrators, resonators, or filter crystals. They are all resonators; but some are used in oscillator-circuits to play a part in controlling their frequencies, while others are used to show their resonance effects while the driving voltage is controlled in frequency by some source independent of the crystal.

In an oscillator where the natural ability of the quartz resonator to establish the timing of pulses makes it successful in imposing its mechanical characteristics on the less headstrong remainder of the circuit, the response of the crystal, its current in relation to voltage and frequency, is no different at any given frequency from that which it would demonstrate if the control of the frequency were in other hands entirely. The piezoelectric circuit response of the crystal to whatever voltages are placed upon it is always purely that of a resonator. Its reaction is characteristic of all resonator reaction whether electrical, mechanical, or acoustical, and includes an amplitude and phase-angle of response which depend on the relative frequencies of resonance and of drive in relation to the Q of the resonator.

In another common use, piezoelectric crystals are elements of the electric wave-filters which serve in carrier telephony, and here again the function of the quartz is merely to respond as a resonator. The crystal, in this case, is no more the filter than is the crystal in the oscillator-circuit the oscillator. The confusion of terms presumably comes about from the synonymous terms "oscillation" and "vibration." Both circuit and crystal are in oscillation. Best usage, however, reserves the term "oscillator" to mean oscillation generator. A complete vacuum tube circuit, with or without a crystal element, serves as the oscillator or generator. Although the crystal "oscillates," "vibrates" is preferred, for the crystal is a resonator.

A principal difference between a vacuum tube oscillator which has a crystal in a place of control of frequency and one not provided with crystal-control lies in the range of frequencies over which the oscillation may be varied by adjustment of some variable element such as the tuning condenser or by chance circuit disturbances. As the condenser-dial is turned, the oscillation frequency of a circuit not controlled by a crystal may usually be varied over a wide range, commonly severalfold.

C. *Crystal-Controlled Oscillators*

There are many types and designs of oscillator circuits for using the crystal's controlling influence. The more common types, at least among those used in radio communication, place the crystal unit across a condenser in the circuit which, thus being in parallel with the crystal dielectric, serves merely to increase the total capacitance shunting the motional properties of the crystal. This combination has an extreme variation of its impedance over a very small frequency range, for within a region a hundredth of a per cent or so above the frequency of mechanical resonance of the piece of quartz (imagined isolated) the impedance of this parallel combination may vary tens of thousandfold. It is the extreme sensitivity to frequency which the impedance (strictly the reactance component) of the crystal shows, whether shunted or not, which is responsible for the extreme variation of its reaction on any oscillator which is not too remotely coupled to it and whose frequency would be likely to vary through the resonance region of the crystal if uncontrolled. Upon this feature depend its control both of oscillator frequency and of the sharpness of boundaries of the bands of electrical filters.

It is the nature of one type of oscillator-circuit that it oscillates at the frequency at which this parallel combination of motional and dielectric branches, including the capacitance external to the crystal, reaches its highest impedance. Another type of circuit oscillates at the frequency of lowest impedance of the crystal, which is its frequency of mechanical resonance. Because of the character of the resonance effects in the equivalent circuit, these two types of oscillators are commonly described as using the crystal in parallel resonance and in series resonance, respectively.

A principal example of the series resonance type of oscillator is the bridge-type designed by Meachen which is used principally for oscillations of highest precision of frequency. In another, the crystal is placed in series with the coil of the tuned circuit of a Colpitts oscillator.

The parallel type of oscillator appears in two common forms. In one, the crystal is located between the grid and the filament of the vacuum tube; in the other, between grid and plate. The frequency of parallel resonance is always higher than that of series resonance of the crystal;

thus the same crystal would control oscillations of slightly different frequencies in the series- and in the parallel-resonant connections. The amount by which the parallel-resonant frequency exceeds the series-resonant frequency for a given crystal depends upon the dielectric capacitance of the quartz and that of the external circuit, and may be as large as several kilocycles per second for an eight megacycle per second crystal, or may be as small as, say, fifty cycles per second. The larger the total parallel capacitance, the smaller is this difference in frequency between series and parallel resonances.

Differences in equivalent motional-impedance properties exist among crystals of approximately equal size and shape because of differences in their effective piezoelectric properties, such as arise from twinning, or from differences in cut or in the details of the complex vibration pattern. As a result, the displacement of the parallel-resonant oscillation frequency from series resonance for the same total capacitance load may vary from crystal to crystal of the same type. It is for this reason that a group of crystals all ground to give identical oscillation frequencies in a given oscillator of the parallel resonance type may show a considerable spread in their oscillation frequencies in other oscillator-circuits having a different capacitance, whether by design, or resulting from manufacturing tolerances. For such a group of crystals, their mechanical resonances might show a considerably larger scattering. Unless special attention in manufacture is given to the magnitude of the difference in frequency to be experienced in oscillation in a series-resonant connection and in a parallel connection across some stated capacitance, it cannot be assumed that close agreement between two crystals in controlling frequency in one circuit will result also in their agreement in frequency in a different circuit. It will perhaps emphasize the point to state that it is the accepted practice in marking the frequency on crystal units for use in communication equipment to indicate the nominal frequency of oscillation in a standard oscillating circuit which places a stated capacitance or a stated characteristic impedance load across the crystal. This nominal frequency is not a characteristic of the crystal's mechanical resonance alone, but assumes its use in a specific electrical connection, and the crystal's use is valid only in connection with an equivalent load.

It may be noted in further reference to the valid use of a crystal that there are slight differences in the frequency position of the crystal's resonance itself which are associated with the amplitude of vibration of the quartz, but whose explanation is not as yet clear. Over and above those changes which can be ascribed to the heating of the quartz through its own dissipation of vibrational energy or that in the mounting mechanism, there appears to be a lowering of the resonant frequency as well as a corresponding change in the impedance properties of the crystal at any fixed frequency near resonance when the crystal is introduced into a second circuit which is identical to the first except that it places a greater voltage across the crystal. The change in frequency is not large enough to be troublesome when frequency tolerances are large, but will become a factor in the application of crystals of tolerances greatly reduced in comparison with those which are now common in communication equipment. It can be a critical factor in the adjustment and frequency stabilities of precision crystals and imposes stringent factors in the using circuit, requiring that crystal currents be kept very small.

III. THE IMPORTANCE OF CONSTANT FREQUENCIES IN COMMUNICATION

A. *Carrier Current Versus Simple Telephone Circuits*

About thirty years ago modern telephony began to multiply significantly the number of conversations which could make simultaneous use of a pair of telephone wires. By the introduction of several carrier currents, each of a frequency well above the highest frequencies of the voice, and each carrier frequency well separated from the other, it became possible, by impressing the characteristics of several voices upon these several carriers, to guide these latter by their frequencies rather than by the ordinary voice-current wires so as to offer channels of communication which transcended the single pair of telephone wires. With the voice impressed upon a high frequency carrier current, a branch circuit selective of the frequency range of that particular carrier would pass that voice into the branch and reject another which was impressed upon a different carrier frequency. In this manner, the pair of telephone wires reaching from city to city in long distance telephony frequently serves as the common circuit over which a number of channels of communication, which have been gathered in over separate pairs of wires from local subscribers, are routed between remote points, each channel having a different characteristic frequency range on the common part of the circuit.

The key to the successful operation of carrier telephony is the ability to translate the frequencies which are present in the voice currents to a corresponding band of frequencies placed higher in the frequency spectrum, that is, to the vicinity of the carrier frequency. And again, at the receiving end of the circuit, the voice on the carrier must be stepped down again in frequency to the voice range. The process known in communication engineering as modulation takes care of the lifting up of a band of voice frequencies to the level of the carrier frequency or of dropping it down again to voice frequency levels.

B. *The Carrier Principle in Radio Telephony*

Wireless communication is based upon the property of electric circuits to radiate their energy more effectively as the frequency of the electric current is higher. Low frequency currents have relatively little effect away from the immediate vicinity of the wires of their circuits. For each high frequency a fraction of the power of the current, which depends on the geometry of the circuit as well as the frequency, departs from the vicinity of the circuit and radiates off as radio waves. The voice is transmitted in radio as a modulation superimposed on the high-frequency oscillation of the radio transmitter and radiates from the station impressed upon this carrier radio wave. The frequencies to which voice frequencies are stepped-up in radio vary from a few tens of thousands to hundreds of millions of cycles per second. Successful operation imposes close restrictions or control of frequencies in the step-up and step-down processes.

C. *Precision of Frequencies Essential*

Enough has been stated to suggest that there is need for controlling the frequencies of radio oscillations which are to be used as carriers to some degree of precision. The susceptibility of ordinary circuit type oscillators to disturbing influences, which cause frequencies to change or to wander, is relieved by putting the control in the hands of a crystal, and thus packing into a very small space the assurance that frequency drift will be within narrower limits.

In helping to set the path which the message on a given carrier will take, crystals sometimes play more than one part. They not only determine the frequency of the carrier and hold it so that it does not shift to the point of possible confusion of identity with and interference with an adjacent carrier (nearby frequency), but they also sharpen up the selectivity of filters so as to let through to a given branch circuit only the intended modulated carrier while discriminating against others. The crystal makes possible in both of these ways the closer packing of channels among the available frequencies of the radio spectrum. Thus not only does one group of crystals determine the frequency gate-posts between which the modulated carrier must pass, but another crystal establishes the carrier frequency which assures that when modulated it will successfully pass through the gate.

In some uses it is the vibratory current in the crystal which after being built up to greater power in later stages of the transmitter becomes the actual radiation. In others, the crystal in a feeble oscillator-circuit serves merely to establish a reference frequency against which the transmitter oscillation is compared, or to which the latter is either manually or automatically adjusted. Crystals for use in such reference oscillators are often referred to as calibrator crystals. Their frequencies may be used to calibrate reference points on the dial of the master variable oscillator so that a chart of its frequency, in terms of dial settings, can be used with greater precision because of the corrections determined for these reference points.

Another use of a crystal oscillator is to keep time rather than to furnish a frequency for reference, although the two are alike in their aim for constancy of frequency. When its successive oscillations are to be added up and a count kept, as in the crystal clock, the interest may be in the total count of vibrations rather than in the instantaneous rate of vibrations. The GT-cut crystal in a bridge-type oscillator has proven itself to be the most precise standard clock. An inherent feature of the crystal clock, in view of the small sizes of pieces of quartz available, is the existence in the clock oscillation circuit of small subdivisions of seconds, commonly as small as a hundred-thousandth of a second. These are valuable as reference points in time, whereas it would be impracticable to identify any phase of the swing of a seconds pendulum to any such precise instant.

D. *Tactical Benefits from Crystal Control*

Where two radio sets must communicate with one another, it is a relatively simple matter, if somewhat time consuming, for either operator to vary his tuning in order to locate the frequency which the other is using and thus to establish communication. The resulting frequency is, however, likely not to be in any absolute sense that which has been assigned for the channel of their communication unless some reliable reference frequency is available to them in determining the channel. The process of searching for the signal from the other party offers, furthermore, the surest means of upsetting an orderly plan of channel spacing and of introducing, as a consequence, interference between stations. In the absence of good frequency control, considerable drifting or swinging of carrier frequencies around their nominal value is the rule and such chance drifting of one carrier only makes more necessary the search, or adjustment, on the part of the second station. The function of the crystal in controlling the frequency of the radio set is to assure that the radiation sent out by the first station is on the allotted channel, and also, when so used, to assure that the receiving station is attuned to that same frequency without search. The receiving crystal is of such a frequency as to step down just the particular frequencies of the carrier channel it is intended to receive to the level of an established lower frequency gate or filter so that after its isolation from possibly confusing frequencies its conversion into voice may proceed.

When a number of radio sets must be brought into frequency agreement so that each can talk with any other of the group, the process of successive adjustment of all to the chance or intentional changes that may occur in one of the sets becomes extremely laborious and time consuming. It is here, particularly, that the advantages of fixed frequency location of channels by crystals are predominant. By using crystals, positive communication is provided without search on the instant of bringing the appropriate crystals into the several circuits. Furthermore, the energy radiated by each of the sets is within the allotted channel and any interference which these waves cause to other communications is characteristic of the system of channel allotment rather than of an uncontrolled swing of the carriers.

The speed and simplicity of the operation of crystal-controlled circuits, the fact that they require little training in their use and usually do not require operators experienced in the technical side of radio, and their ready adaptability to push-button operation and selection of channels are large factors in the popularity of crystal-controlled equipment. Some simplification of circuit design is made possible by making available to each set a number of crystals so as to give it access to a multiplicity of communication channels, if not to the infinite degrees of off-channel operation.

There may be, however, circumstances which warrant the shift in channel frequency to a nearby free region when the assigned operating frequency suffers from interference. The designer must usually make his choice between providing for communication on any frequency in the range without crystals and providing only predetermined channels. Only for the latter case may crystals be provided, since crystals are not available with sufficiently variable frequency for the former.

IV. The Importance of the Orientation of Quartz Radio Elements

A. *Orientation for Desired Mechanical Properties*

The dependence of Young's modulus and other elastic constants of quartz upon the direction of the stress in relation to the crystallographic axes is well-known. The detailed mechanism of the mechanical vibration of a piece of quartz in any mode involves the values of the elastic constants which relate to that mode, the density of the quartz, and the geometry and dimensions of the piece, as well as the constraints imposed by the mounting. The dependence of a particular elastic constant upon direction results in the variation of the resonance frequency which it determines, with slight change in angles of cut. Owing to the interlocking dependence of the main strain upon accompanying minor strains in other directions the complete detail of the combined motion and the frequency of the resonance actually depend simultaneously, in most cases, upon several elastic constants and dimensions.

A mechanical mode of vibration is, except in what are usually wholly negligible ways, entirely a mechanical problem, and the ability of a plate or bar to show mechanical resonance at a given frequency depends upon the appropriateness of elastic constants, orientation, and dimensions to the setting up of a standing wave system at that frequency. The manner of applying the external forces which might set up the proper strains is not important to the description of a mode of possible resonance, although before such a mode can be physically excited some driving mechanism must be found.

It is characteristic of elastic solids that under a stress applied in one direction, the strain which that stress produces in this same direction is accompanied by other strains in other directions. The most familiar example of such strains is the sidewise shrinking of a bar or wire when stretched lengthwise, a property expressed in Poisson's ratio for the material. In crystalline media, as distinguished from isotropic, these cross-strains may appear unsymmetrically as is evident from a study of the elastic constants of the crystal. They become important in quartz crystal vibration where in resonance the cross-strain may become large enough to be a significant fraction of the main-strain. If the cross dimensions are appropriate to their establishing a second set of standing waves superimposed upon the first, the interlocking effects between these two become exceedingly complex. Dust patterns and other means of detailed study of the motion over the face of a vibrating quartz plate indicate that the modes of motion are very complicated indeed, and the familiar dust patterns on Chladni plates are intricate enough without the additional effects of aeolotropism. Because of the minute scale of the detail of the wave patterns on a quartz plate, they shift with the slightest change in crystallographic orientation or in size or shape, and the circuit behavior of the crystal changes accordingly.

B. *Predimensioning: Precise Duplication of Orientation and Dimensions*

The precise mathematical solution of such a complex vibrational system is probably hopeless. The practical solution for radio quartz plates is to prepare a model plate, adjusting it by methods which are partially "cut and try" until it gives satisfactory performance in the radio circuit, or better, gives the combination of intrinsic properties desired. This model is then copied in production, exactly duplicating the orientation, geometric shape, and the dimensions. This use of a model and precisely copying it is commonly referred to as the predimensioning method of manufacturing quartz plates as distinct from the custom-making adjustment of each crystal separately until it gives adequate performance in the radio circuit. The former method results in a degree of homogeneity between crystals which are produced to the same dimensions which is entirely lacking in the latter method of production.

C. *The Effects of Orientation on Piezoelectric Properties*

Although, as has been indicated, the mechanical vibrations of a quartz plate are characteristic of mechanical properties alone, the necessity of coupling such mechanical vibrations to an electric circuit requires the use of preferred directions in the quartz for the principal strains in the vibration which can produce piezoelectric currents at suitable electrodes. The optic-axis direction, for example, is entirely devoid of electrical coupling to strains in the quartz since this direction shows no piezoelectric properties. Vibration of a plate cut perpendicular to the *c*- or Z-axis, a Z-cut, as it would be called, can neither be driven electrically by a field along Z, nor can electrical effects of any such vibration be picked up by electrodes symmetrically placed on Z-faces of the plate.

In general, electric fields which are perpendicular to the optic axis are the most strongly coupled to mechanical strains, although even then only to certain particular strains. Quartz plates cut to take advantage of these maximum directions of the piezoelectric effect are the X-cut and Y-cut plates, named from the fact that the normals to their principal surfaces are parallel to the X- and Y-axes of the quartz, respectively, the *a*- axis of the crystallographer and its normal. It is in the nature of the piezoelectric properties of quartz that electric fields parallel to an X-axis, as in an X-cut plate, are associated with stresses or strains of a compressional type along the directions of X and Y, one being extensional while the other is compressional, as well as with an added shear type of strain. The shearing layers sliding with respect to each other may be thought of as either XY-planes showing relative displacements in the Y-direction, or as XZ-planes showing relative displacements along Z; in any case the displacements in the shear are perpendicular to X.

The effect of a Y-field, on the other hand, as in a Y-cut plate, is to produce two superimposed shearing stresses, one in which all displacements are perpendicular to Y, and the other all perpendicular to Z. The one may be thought of as the sliding of neighboring YZ-planes in the Z-direction, or alternatively of the sliding of XY-planes in the X-direction. The other shear may be viewed as the relative displacement of XZ-planes in the X-direction or YZ-planes in the Y-direction.

The several stresses and strains are related through the so-called piezoelectric moduli and/or piezoelectric constants to the electric polarization of the quartz, some to the X- and some to the Y-component of the polarization, and thus to the corresponding electric fields or surface charges. Along with the orientation of a vibrating quartz plate and the detailed character of the mode of the vibration, these constants determine the magnitudes of piezoelectric currents within the quartz, between the electrodes, in relation to the changing mechanical strains in the plate.

D. *The Oblique Cuts*

The continuing development of the art of crystal control has led to the use of quartz plates no longer normal to the plane of the X- and Y-axes. In general, the piezoelectric coupling between vibration and circuit is less as the orientation of these plates departs farther from the normal, although the mechanical properties show no corresponding deterioration, but only change. Specific orientations are selected to take advantage of the compensating effects between the temperature coefficients of the several elastic properties which play parts in the vibration so that the resonance frequency of a plate may remain much more constant over a range of temperatures than does any one elastic constant of quartz. At certain other inclinations, the cross-coupling of one type of elastic strain to another vanishes, and plates so cut as to take advantage of this are much more free from the problems of complexity of the mode of vibration than plates not so cut and may even retain this freedom over a wide temperature range.

Shear vibration is the common type among those oblique cuts which may be thought of as derived from Y-cut plates by rotation about X. Longitudinal modes characterize those bars which are derived by a rotation, about X and about their length, from X-cut bars whose length lies along Y. The several orientations of these inclined "cuts" need, in general, to be held with great precision in order to take full advantage of the temperature compensating mechanism or of the interrelations between modes, although some small degree of misorientation can often be balanced by slight modification of the dimensions.

V. THE RANGES OF THE CHARACTERISTICS IN QUARTZ CRYSTAL UNITS

In a survey paper, intended for readers in fields other than physics or radio, it seems desirable to include a brief analysis of each of the many variables which one finds among crystal units, in order to permit the reader to classify more readily the many types of crystal units which he may encounter. Except when the holder is made of clear glass, as is sometimes the case, little is evident as to the crystal itself from the outside of the crystal holder, of course, except perhaps for such markings as indicate the nominal frequency of the oscillation which the crystal may be intended to control. The limitations of space to which the unit may be adapted and the characteristics of the mechanical fitting to the radio set will be evident, but the size of the holder may be misleading as to the size of the piece of quartz which it contains, and its external features give no indication of the type of mounting.

A. *Size of Crystal Plate or Bar*

Quartz plates range in thickness from six or eight thousandths to half an inch, with fifteen to thirty thousandths as the sizes which have probably been made in the greatest numbers. Face shapes are most commonly square, or rectangular near square, with dimensions of the order of half an inch on a side, while plates as small as one eighth inch square and as large as two inches square are standard items. Bars are used at present in much smaller numbers than plates, although this is probably owing to the frequency range, three to nine megacycles per second, which has seen greatest recent application. Filter uses are primarily for bars. Bar sizes have run from about $3/8'' \times 1/8'' \times 1/16''$ to $3'' \times 1/2'' \times 1/8''$, with the most common sizes in the middle of the range.

B. *Frequency*

Crystals are made to resonate at frequencies scattered all the way from a few thousand to more than one hundred million vibrations per second. All crystals show more than one frequency of resonant response; most have a large number. The predominance of the desired resonance in its particular region of the spectrum must usually be supplemented by circuit preferences for that region over others in order that the crystal-controlled oscillator shall make use of the intended resonance. This resonance may not be a fundamental mode of its type, in which, of course, the frequency determining dimension is a half wavelength in the quartz, but may be some overtone in which the crystal is several half wavelengths thick, or long, as the case may be. In overtone modes the crystal acts as if subdivided into sections, each of which vibrates almost identically, with alternate sections in opposite phase.

C. *Type of Vibration*

In some crystals the vibration is predominantly extensional and contractional along a given dimension of the plate or bar. In others, the motion is of shear type. In these latter the shear may be, in some cases, a distortion of the major faces of the plate, while in other cases the undistorted major faces may be thought of as sliding with respect to each other along their planes. These types of shear are referred to as face-shear and thickness-shear, respectively.

Still other crystals are used for their resonance in flexural vibration. Here again there are two planes in which the flexure may occur, as well as long series of overtone modes for each. A crystal cut like a thin lath may bend the easy way and resonate at a very low fundamental frequency, or it may select the stiffer flexure in a plane at right angles to this and a fundamental mode of resonance at a much higher frequency. The type of vibration which is excited in a given case depends partly upon the method of mounting and the points of constraint which this determines, and also upon the cut and the disposition of electrodes. More elaborate arrays of these latter are used for exciting flexural modes, and likewise for overtones of most types, than for the fundamental modes of shear or of extension.

If the electric field is applied in the direction of the dimension which determines the length of the principal standing wave system, only odd overtones can, in general, be excited, for in only these cases are opposite charges on the two electrodes produced by the motion. A well-known crystal of this type is that frequently called the "third-harmonic" AT-cut plate. This vibrates in thickness-shear in three layers at a frequency which may be 12 mc/sec, whereas the plate is of a thickness to vibrate at about 4 mc/sec if its fundamental thickness-shear resonance is excited. Frequencies of oscillation circuits as high as 197 mc/sec have been controlled using the fifteenth thickness mode. Special types of oscillator-circuits are required to select the desired overtone mode of vibration from among the extensive series of possible modes.

The practice of designating these vibrations as "harmonics" may lead to some confusion between mechanical overtones of crystals and the harmonics of the vacuum tube oscillator. As is the case with all vibrating solids, the several overtones of a given fundamental type of vibration do not follow the harmonic series strictly. On the other hand, there are cases in which crystal oscillator-circuits are designed to emphasize some exact harmonic of the frequency of the crystal oscillation, as where the harmonic is produced in the process of distortion of the alternating current by the vacuum tube. In the one case, the crystal and circuit oscillate at the overtone frequency and neither the motion nor the current at the fundamental frequency is involved. In the other, the crystal and circuit oscillate at some crystal frequency and a branch circuit, or perhaps some later stage of amplification, selects a harmonic which has developed in tube distortion. The designation "third mode (of thickness-shear)," for the case described in the preceding paragraph, would avoid the confusion and reserve the term "harmonic" for the case of distortion of alternating current wave-form, where its use is well-established and is proper.

The following breakdown of the frequency spectrum into the modes of vibration which are perhaps most commonly used in the several frequency ranges may be found useful:

Frequency range (cycles/sec)	*Type of Vibration*
2,000– 30,000	Flexure
30,000– 100,000	Extension and compression of bars
100,000– 1,000,000	Face-shears of plates
1,000,000– 15,000,000	Fundamental thickness-shears of plates
15,000,000–100,000,000	Higher-order modes of thickness-shear

There are no sharp boundaries between these ranges, and a good deal of overlapping exists. The figures given are intended to be merely suggestive.

In the complex vibration which characterizes many of the common and useful resonances, particularly the thickness modes of plates, there is superimposed upon the predominant type of motion a complex superstructure of overtones of other fundamental modes, some of which represent other types of vibration, and many of which are resonances along a different dimension than that of the principal motion. The entire plate vibrates at one frequency but the motion, in some parts, may be either just opposite to that in other parts, or perhaps greatly increased or greatly reduced in comparison with neighboring regions.

D. *"Cuts"*

The orientation of a quartz plate or bar is referred to either by the angles which the normal to a major face makes with the crystallographic axes or by a characteristic name which indicates a cut having special properties. Thus the AT- and BT-cut plates are inclined $+54° 45'$ and $-41°$, respectively, from a Z-cut, the rotation being about X. These cuts determine frequencies for their fundamental thickness-shear modes which have relatively small dependence upon temperature. Similarly, CT- and DT-cut plates are inclined from a Z-cut by angles of $+52°$ and $-38°$, respectively, about X, and show small dependence of their face-shear frequencies upon temperature. The convention of signs now used gives positive signs to counter-clockwise rotation as seen from the positive end of the axis of rotation for a right-handed axial system, clockwise for a left. A right-handed axial system is used for right quartz, and left-handed for left quartz. The positive end of the X-axis in either quartz is identified by an edge of the prism at the ends of which *s*- and *x*-faces are possible.

The angles given in this paper are not those by which the "cuts" referred to are best known, but rather their complements. The more commonly used designations, such as +35° 15′ for AT- and −49° for BT-cuts, are the inclinations of the plates themselves to the Z-axis rather than of their normals, as are used in this paper.

Considerable confusion regarding the definitions of right and left quartz and the senses of axes and of positive rotation pervaded the radio engineering literature on quartz crystals prior to 1940, when general agreement was reached to use the mineralogists' definitions regarding the nomenclature of the enantiomorphic forms and the convention of signs described above. An Institute of Radio Engineers Committee Report regarding such a standard convention is in process of publication. In order to provide an unambiguous system of specification of the orientation for quartz plates or bars cut at any inclination, three rotations are listed about three axes, to be performed in order. By these, starting from the standard reference position of a Z-cut rectangular plate with its length along X, any position of the plate may be specified. All rotations of the plate, assumed to be a rectangular parallelopiped, carry with them a rotated set of axes parallel to the edges of the plate. In their rotated position these axes are primed, as X′, Y′, and Z′ after a first, and double primed after a second rotation. As already stated, for a right quartz, and a right-axial system, positive angles appear as counter-clockwise when viewed from the positive end of axis of rotation.

The first rotation is performed about Z, and is called ϕ; the second, θ, about Y′; and the third, ψ, about Z″, which is also Z‴. Although a final designation of orientation is unambiguous, it is possible to arrive at two or more designations for the same physical orientation depending upon the choice of a plus or minus 90° angle for ϕ in the first rotation by which Y′ is placed along X preparatory to the second rotation. Thus the BT-cut plate may be alternatively designated +90°, +41°, 0° (or 90°) or −90°, −41°, 0° (or 90°). There is some reason for preferring the second which brings Y′ into the same sense as X instead of the first where Y′ is in opposite sense to X. The −41° designation of θ is also in agreement with the numerical description for the BT-cut given earlier where only the conventional mathematical procedures for a right-handed axial system were used, without reference to the complete I.R.E. system of three rotations.

The use of a complete mirror image of the axial system and senses of angles to conform to the change in enantiomorphic form to left quartz provides that the BT-cut in a left quartz carries the identical set of angle indices, and each other cut, likewise, is identically described in either quartz.

Other well recognized cuts beyond those already described include GT-, ET-, FT-, and NT-cuts, and the so-called −18° and +5° bars, but reference should be made to other papers for characterization of their properties.

E. *Temperature Coefficients of Frequency*

The frequencies of crystal resonators vary with temperature at different rates at different temperatures, particularly where approximate constancy of frequency over an extended temperature range is secured by compensations within the quartz over that range, as in specific cuts. As a result, except where the crystal is to be held to the close vicinity of one temperature, the total variation of frequency is usually of more interest than the temperature coefficient at any one temperature. For curves showing the characteristic variation of frequency with temperature for the several cuts, the reader is referred to the original sources. The frequency of a BT-cut plate follows a curve which is roughly a parabola with the vertex showing the maximum frequency located at a mean temperature in the total temperature range of interest. The temperature at which this highest frequency occurs is controlled by choice of the precise orientation for the cut, being about 30°C. for a −41° BT-angle, and higher as this angle is larger. A departure of about 0.025% from the highest frequency is inherent in the characteristic curve for temperature variations of 70°C. either upward or down from the chosen mean temperature.

The frequency drift curve for varying temperatures which characterizes an AT-cut plate is less well determined. Its shape depends to a very considerable extent on the precise dimensions chosen unless the plate is very thin in comparison with its length and width. Judicious choice of dimensions appropriate to a specific orientation will permit a relatively flat frequency curve over a large part of the 145 Centigrade degree range for which many manufacturers are making crystals. The possibilities of considerably reduced frequency tolerances from using this cut in preference to the BT-cut for frequencies in the 5 to 10 mc/sec range have not yet been exploited. Units departing from a mean frequency less than twenty parts in a million over a temperature range 145 Centigrade degrees wide have been made, but manufacturing tolerances for this extreme frequency precision may well be too close to be met in production. The curve for any cut is susceptible to the modifying influences of cross-coupling for any arbitrary dimensions of the plate, especially when the plate is thick (a tenth or more of its length or width). This distortion is particularly common for AT-cut plates where the lower frequencies used often call for extreme thickness.

F. *Temperature Range*

In the military use of crystals, where frequently the crystal temperature is not controlled, the limits to which ambient temperatures may run force extreme requirements as to the limits of angular tolerances which can be permitted in manufacture. The characteristic curve for the BT-cut crystal is illustrative of the problem, for it makes no allowance for internal heating of the crystal caused by its vibration. Circuits which cause the crystal to dissipate more than a hundred milliwatts offer special difficulties on this score since the frequency follows the crystal temperature, of course, rather than the ambient for which frequency curves are commonly drawn. Also, the crystal unit may have to operate in an ambient of wider range than the radio set, as crystals are sometimes placed in compartments which warm up during the operation of the set. The extension of the crystal's operating range may become considerable if the set must operate from a cold start in the coldest weather as well as after a warm-up period of operation in the hottest weather. This requirement may well add 25 to 30 Centigrade degrees to the operating range, and the internal heating of an active crystal in a vigorously driven set an additional 25° or more. The BT-curve, although adequate for $\pm 0.02\%$ frequency limitations over 145 Centigrade degrees when proper design considerations are observed, scarcely permits the operating of crystals within these tolerances over the full range of $-55°$ to $+70°$C., which has been laid down as the ambient for some equipments themselves, unless care is taken to avoid extremely active crystals and to locate crystals within the equipment where they will not be warmed up by the tubes. It is the most active crystals which are driven most violently and, therefore, heat up the most. To include some allowance for compartment heating, crystals are often specified to maintain tolerances over the wider ambient temperature range of $-55°$ to $+90°$C.

G. *Load Circuit*

The circuits in connection with which crystal units are to operate impose very definite limitations on the properties of the crystal unit. One of the most important circuit characteristics is the impedance across which the crystal is to be connected. Many equipments which use the crystal in the parallel resonance connection place it across a capacitance in the circuit, and the magnitude of this capacitance determines the location on the crystal resonance curve of the frequency at which oscillation is to occur. Hence, in finishing crystals they are adjusted to provide the desired frequency when used in connection with the appropriate value of capacitance. Such values range from ten to a hundred or more micromicrofarads. It is characteristic of a fixed capacitance load that the magnitude of the load impedance varies inversely with the frequency. In multichannel equipments where a number of crystals are to be provided covering a wide range of frequencies, the lower frequency crystals are thus operating into a relatively large circuit reactance while the higher frequency crystals face a small reactance.

Some circuit designs, on the other hand, place an impedance across the crystal which follows a different law with frequency than that of a fixed capacitance, and the crystals made for such equipments require to be adjusted to frequency under the appropriate impedance load condition which is specified for the frequency in question. Among the several series of commonly used crystals in military communications, some are intended to operate across a stated capacitance for all crystal frequencies and others across a particular combination of inductance and capacitance. It is in cases such as the latter, particularly, that circuits which are exact copies of the oscillator in the using equipment need to be provided for the manufacturer of crystals in order that he may adjust each crystal to the circuit impedance which the "test set" shows at that frequency. It is somewhat more simple to duplicate from characteristics set down on paper the testing conditions where the circuit load is a fixed capacitance than for a more complex load.

H. *Activity*

In finishing crystals, the manufacturer is usually particularly concerned about producing units which are sufficiently "active" to meet the requirements of the using set. There has grown up out of this concern of the manufacturer, and also out of experience with "dead" crystals, a common belief that the most active crystal units are always the best, or that high activity itself will result in better performance of the radio equipment. Such is not the case. A crystal's activity depends upon its electrical impedance. In the design of circuits, all other elements than crystals have their impedances specified within both upper and lower tolerances, and a similar statement of the best value and of its upper and lower limits is equally desirable in the case of a crystal as a circuit element, as indeed is already done with precision crystals in the low frequency ranges.

There are two principal reasons why the specification of an upper limit for crystal activity has not been used more widely. One of these is that for the crystal's position in the oscillator-circuit, particularly when used in the common parallel resonance connections, the saturation characteristics of the vacuum tube tend to alleviate by compensation some of the results of excessive crystal activity. Also, the crystal manufacturing problem is a more difficult one with the additional tolerance in the specification unless predimensioning methods are used. With those crystal units where close tolerances on the impedance (activity) characteristics are part of the design, the using equipment is in a position to incorporate features into its own design which take advantage of a more precisely defined crystal unit.

Following a development by Fair, it is becoming the practice in the study of the performance of the crystal units, if not yet in specifying them, to use the performance index (PI) of a crystal unit as a measure of its intrinsic activity properties. Activity, as it has been commonly used, refers to the d.c. voltage developed in the grid circuit of a vacuum tube when it is oscillating under crystal control. More active crystals develop larger grid voltages. Activity, when defined in terms of oscillator-circuit voltages, is unfortunately dependent upon both crystal properties and oscillator-circuit properties and varies greatly with the vacuum tube and the line voltages used. The activity of a crystal in any given oscillator-circuit is proportional to the impedance of the crystal when in parallel resonance with the circuit load at the oscillating frequency. This impedance, in ohms, is taken by Fair for his PI and is the crystal's contribution to the so-called activity in any parallel-resonant oscillator. In general, this performance index has its smallest values when the crystal is connected across the largest values of circuit capacitance. Values of PI run from a million ohms or more down to a few thousand ohms, a large part of this spread being required for the range of circuit capacitances alone. The PI is proportional to the Q of the crystal, among other factors. The predimensioning method of manufacture is capable of holding the PI and the Q for crystals of any one frequency to within a variation of a few per cent over the entire production.

I. *Voltage and Power Dissipation*

Not only does the high-frequency voltage which the oscillator applies across the crystal depend upon the circuit and upon the vacuum tube which is used, but in the parallel-resonant connection, at least, this voltage is approximately proportional to the activity of the crystal, or to its PI. Thus, a crystal just active enough to pass the minimum specification may in its intended oscillator be driven at, say, twenty volts, while in the same circuit connection a crystal four times as active would develop seventy-five or eighty volts. When circuits using different tubes and placing different capacitances across the crystal are considered, the voltages which are placed across crystals range from ten to one hundred fifty volts.

Whereas the voltage itself is probably not important, except as excessive voltages cause glow discharges and arcing between the crystal surfaces and electrodes, or between the electrodes themselves, the heating of the crystal in excessive vibration sets a severe limitation on the frequency tolerances attainable, as already stated. The power dissipated within the crystal plate or at points of friction in its mounting is given by the ratio of the square of the voltage to the PI in ohms and is expressed in watts. Among the types of crystals which are most common in military communication equipment this power dissipation varies between 1/20 and 1/2 watt. In the development of crystal units to closer frequency tolerances, it will be necessary to keep the power dissipation within the crystal unit to a low figure, perhaps well below one hundred milliwatts. It will require either the use of circuits which do not develop large voltages across the more active crystals, or the specification of an upper limit of crystal activity in manufacture, and/or the provision of means for more ready conduction of the heat developed within the crystal out to the ambient. A rather loose upper limit on activity has already been in effect in the trend to the use of smaller quartz plates without a corresponding change in the minimum activity requirements.

Much of what has been included in the last two sections refers principally to high frequency crystals of military communication equipment used in the parallel-resonant connection. In their series-resonant use, the voltages across equivalent crystals would be very small indeed. The series-resonant resistance of half-inch square pressure mounted crystals in the five to ten megacycle range varies from five to perhaps twenty ohms. Variation of this resistance inversely proportional to the square of the frequency of the plate is inherent for plates whose vibrations are unconstrained. For plates lower than 5 mc/sec, where owing to their extreme thickness clamping at the corners seriously interferes with the freedom of vibration, resistances considerably in excess of the values expected from this inverse square law are found. The activity property of a series-resonant crystal is often described in the terms of its series resistance, and as the latter is made smaller, the crystal is more active. This is in contrast to the association of greater activity in parallel-resonant crystals with their higher equivalent series resistance at parallel resonance.

In applications of crystals as circuit elements at frequencies below 500 kc/sec, there has been much success in controlling both crystal parameters and the properties of the using circuit to a relatively high degree of precision. In this field the total number of units produced is almost insignificant in comparison with the numbers of higher frequency crystals used in military communication equipment, and there has been greater detailed study of the performance and limitations for their more exacting use. Furthermore, precision measurements of crystal properties are easier to make and crystal vibration modes easier to control and predict at the lower frequencies. Comparable measuring instruments and techniques are only just now beginning to appear for the determination of the properties of high frequency crystals, and great progress in this field is anticipated over the next few years.

J. *Finish, Surface, and Mounting of Quartz Resonators*

In the early experience with crystals for military communication, crystal surfaces were not etched after grinding, or at least not etched to a sufficient depth, and a characteristic ageing of crystal units ensued. Under the effects principally of water vapor, but probably also of temperature changes and vibration, the deterioration of an abraded surface was found to proceed to such extremes that the thinner crystals would lose a significant part of their quartz and thus depart from their intended frequency. This surface disintegration progresses over hours or years, depending largely on humidity conditions, and it so limits the stability obtainable from ground crystal surfaces that the practice of finishing high frequency crystals by etching to frequency is now in almost universal use.

Many crystals are plated, the plating providing electrodes in close proximity to the quartz itself and making the full voltage applied by the circuit across the electrodes effective in driving the quartz without a partial loss in an air gap. The direct effect is to provide a considerable increase in activity beyond that which the same crystal would have if not plated. Unless the plating is made thick, it introduces no evident damping and thus does not lower the Q of the crystal. Electrodes so plated directly onto the crystal make possible wire connections which may also serve as mountings for the crystal. One advantage in the wire-and-plating type of support over the more common pressure mounting is that with the soldering of the connections neither jarring nor time disturb the validity of the electrical connection or change either the points of support or the applied constraint, both of which changes are troublesome in pressure mounted crystals. A shortcoming of the former type of mounting is the failure to provide a heat reservoir of large thermal capacity close enough to the quartz plate to receive by an easy conduction path the heat there generated. Such crystals run considerably hotter for the same activity and in the same circuit than do pressure mounted crystals for which thermal conduction across a very short air gap is fairly effective in preventing an excessive temperature rise of the quartz plate itself.

For neither the pressure mounting which clamps the corners of the plate nor the wire suspension type wire mounting with attachments at two peripheral points is the mechanism of restraint and its influence on the mode of vibration of thickness-shear crystals completely understood or very well controlled. An ideal type of mounting for such nodes would appear to be the support of the plate at a central nodal plane with the edges of the plate perhaps tapered to a supporting knife edge. Such mounting arrangements have been tried but are not in common use.

Less constraint is applied to a crystal in the so-called space mounting. Here the plate rests on one electrode while the second electrode is not quite touching. In the case of the thickness-shear mode, which is the principal type under discussion, the plate is obviously constrained to a degree so long as it rests on one face. As the amplitude is increased the plate would be expected first to make only chattering contact and then at larger amplitude still looser contact with the electrode on which it rests, and in this condition be under less constraint with a slight consequent fall in frequency. In making thickness-shear crystals in the half-inch square size at frequencies in the one to three megacycle range, it is becoming common to use spacer mountings in order that the crystal may develop reasonable activity at these frequencies. The restraining effects of corner clamping in limiting the freedom of vibration at the central area of a plate are much more serious for thick plates than for thin.

K. *Holders*

Crystals of the highest precision are contained in hermetically sealed holders which are commonly evacuated to reduce the supersonic radiation losses of energy from the crystal. The development of comparable mountings for military communication crystals has not kept pace with that for precision crystals and filters.

The common phenolic holder has been the source of a good deal of difficulty in several ways. The phenolics have often been permeable to water-vapor so that the humidity within the holder cavity becomes comparable to the humidity of the ambient after a short exposure even though the neoprene gasket used provides a tight seal. With repeated temperature and humidity cycling, drops of water accumulate within the cavity through a pumping action which results from differences in humidity and temperature between cavity and ambient. Again, particularly at the higher temperatures, vapors released by the phenolic either cause corrosion of metal parts within the holder cavity or are available to condense on the quartz itself when the crystal is cooler than the phenolic. The frequency of the crystal is so sensitive to condensation upon its surfaces that fractions of a microgram produce detectable changes in frequency for the thinner crystal plates as well as introducing damping to interfere with the activity.

Some types of phenolics introduce dielectric losses between the terminals or the pins of the holder, particularly after absorbing water, so that the normally high performance index of a crystal suffers a reduction in its ohmic value due to the shunting action of the poor phenolic dielectric. In some equipments even the d.c. leakage of the phenolic has proved troublesome.

Following the realization of the poor performance of the grades of phenolics formerly in use, much improvement has been found in the use of grades less permeable to water vapor which maintain their electrical resistance and which are free from corrosive vapors.

Despite the improved character of the holders now in use, it is believed desirable to use hermetically sealed glass, metal or ceramic holders for communication crystals, particularly with the thought that the natural trend in crystal control will be toward crystals meeting closer frequency tolerances. The misbehavior of the holders has been one of the principal obstacles in the attainment during a long life of the ±0.02 per cent frequency tolerance over the wide temperature range which many military crystals must meet. In the development of hermetically sealed holders the problem is, in part, to find ways to obtain a seal which is equal to that used in vacuum tube technique while still adaptable to present form factors. There is no desire at the present time to have an evacuated holder for these crystals, but almost complete absence of water and other vaporizable materials which might deposit on the crystal to shift its frequency is regarded as an essential. It is the present view that the most likely practical test of tightness of the hermetic seal is to immerse the sealed holder in saturated water vapor directly following long exposure in a vacuum chamber, the crystal itself to serve as an indicator of the admission of water vapor to the cavity.

VI. A COMMENT ON THE FUTURE OF PIEZOELECTRIC RESONATORS

There are no alternative sources in sight for the enormous values of Q which quartz makes possible in resonators. Thus it would appear that any needs for the utmost in frequency precision and stability will continue to be met by the use of quartz.

There are large areas of the frequency control problem where the ultimate in constancy of frequency is not required and where the choice of a piezoelectric resonator instead of a wire circuit is to some extent one of convenience, cost or space, and where the required performance could be obtained through appropriate sacrifices without the use of quartz. It may continue to be the practice to use quartz in such cases although not pushing its control features to the limit. Much might depend on the continued availability of the supply of quartz. The degree of frequency constancy needed in many applications could probably be obtained using very much smaller pieces of quartz, but difficulties in handling during fabrication and the inherent greater percentage of waste in sawing and lapping tiny pieces are definite obstacles. It is in uses where the highest Q's are not required that some mechanically inferior substitute for natural quartz might well offer the convenience of mechanical frequency control while admittedly providing a degree of frequency constancy lower than that which quartz might provide.

While the convenience of the quartz resonator in portable and mobile radio equipment lies partly in the freedom from temperature control which the peculiar elastic properties of quartz make possible, many of the advantages of crystal control would persist despite the possible necessity for thermostating a substitute crystal if it were developed. In view of the growing practice of mounting in a hermetically sealed holder and shock mounting the crystal on wire suspensions, a new piezoelectric crystal need not necessarily meet the high mechanical standards of quartz.

Quartz itself, particularly as it pioneers in new fields of more extreme frequency precision, or into higher frequency ranges, will probably show that its full powers in these directions have been far from being exploited. To mention just one factor, the problem of the surface stability of quartz which was not considered in its full light until its appearance in the recent experience with ageing units, is well on its way toward clearing the road to the use of thinner and higher frequency crystals; and this same stabilizing of the surface is one of the factors in the attainment of the highest Q's, the extreme values of which are not yet fully utilized.

The existence of the simple and the elaborate designs of crystal units in today's manufacture emphasizes again the two extremes of requirements noted earlier in the comparison between low and high Q materials in their future applications. On the one hand, quartz units made, mounted and sealed with precision according to a well worked out design, give a performance which is consistent to an extreme degree, and with the minimum in frequency tolerances. The use of precision units is amply justified when the application calls for these extreme tolerances, for there is no other way to achieve the required end than by the use of quartz and by the close attention to the great detail in its fabrication and in its adaptation which is required. On the other hand, crystal units at the other extreme in the perfection scale have their proper application as well. For this type of unit it has been amply demonstrated during the past few years that there can be obtained in enormous volume at ridiculously small cost, a unit which is highly useful, and whose properties meet tolerances which, though at least one order less rigid than in units of the precision class among crystals, make it nevertheless a precision device in comparison with other circuit elements.

The systematic development of units in this latter field, however, despite the great progress which has been made, has not received the attention which it deserves. This is largely because of the pressure for production, its enormous expansion under wartime demands, and the necessity for emphasis upon correcting existing designs and upon controlling the quality of the product. The time is now believed to be ripe for studies of the basic circuit properties and circuit behavior of crystals in this latter field, along with the re-evaluation of the designs, and for the development of instruments and measuring techniques for these new components of high frequency circuits. Research and development work in this field is now in a position to capitalize on extensive practical experience which is a guide that was largely lacking a few years ago. In the view of the writer, the high frequency crystal unit is approaching the stage in its evolution where it will become as well standardized and as well measured and specified a circuit component as are resistors, condensers, coils and tubes today. Furthermore, its properties will be similarly stated in terms of conventional electrical units. The reduction of performance to standard electrical engineering terminology, the refinements of design and of processing controls to assure meeting the circuit values found to be desirable and practicable, and the development of a circuit formulary and instrumentation for this new branch of radio engineering represent, however, projects which will require several years for their accomplishment.

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