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Fundamental Techniques in the Frequency Adjustment of Quartz Crystals

by Leland T. Sogn and Catherine Barclay

National Bureau of Standards Circular 480
Issued September 1, 1949

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.
Price 10 cents

Preface

Quartz crystals have in recent years become indispensable components of many electronic assemblies requiring precise frequency control. This frequency control is achieved, however, at a loss of versatility, since a crystal unit will operate only at this single frequency, or at multiples of it. Sometimes due to frequency interference or to other causes, it is desirable to move to another frequency. On such occasions a crystal must either be discarded or have its frequency changed.

There is widespread demand for information about ways to change the frequency of high-frequency thickness-shear crystals. This Circular presents in considerable detail methods for doing so. Although adjustment to lower frequencies is limited to a maximum of approximately 1 percent of the crystal fundamental, there is no similar limit on adjustment to higher frequencies. Literature references are included for the convenience of those who wish to pursue the subject more extensively.

E. U. Condon, *Director.*

Contents

Fundamental Techniques in the Frequency Adjustment of Quartz Crystals

By Leland T. Sogn and Catherine Barclay

Techniques that are required in the art of adjusting frequencies of quartz oscillator plates are dealt with in some detail. A number of the problems associated with crystal finishing are reviewed. Ways to prevent the introduction of erratic behavior, such as sudden changes in frequency and amplitude, are discussed, and methods of eliminating these undesirable characteristics, should they appear, are described. A schematic diagram of a high-frequency oscillator which will give a fairly accurate indication of the quartz-crystal unit performance is included. A simplified concept of the modes of vibration found in quartz oscillators is presented in order that the reasons behind the techniques employed may be better understood.

I. Introduction

There is wide interest in quartz oscillators among people in all fields of electrical communication. The present paper is intended to give detailed instructions that will enable the novice to make minor frequency adjustments. In order that problems may be approached with more assurance, an elementary treatment of piezoelectricity[1] and elasticity is included. It is felt that the most effective use of standard techniques is possible only if the operator understands the basic theory of piezoelectric oscillators, and the reasons why irregular and nonparallel major surfaces and other deviations from symmetry introduce undesirable characteristics, such as sudden changes in frequency and amplitude of oscillation. A knowledge of basic facts will also promote a more intelligent interest in the operations and thereby lessen the mistakes that result from carelessness.

Pertinent information concerning abrasives, lapping plates, and etching compounds is included. A suitable high-frequency oscillator for indicating performance is described, and operating characteristics for acceptable quartz-crystal units are stated. The treatment of the subject has been made as comprehensive as possible in a paper of this length in order that a minimum of time need be spent in securing information from other sources.

Piezoelectric crystals, when strained due to the application of pressure, become electrically polarized; conversely, when placed in an electric field these crystals become mechanically strained or deformed. This phenomenon, known as the piezoelectric effect, is useful in providing coupling between an electrical circuit and the mechanical properties of a crystal. About 10 percent of all crystalline substances are piezoelectric, but a combination of factors has made quartz superior to other crystals as a frequency-control element in most electronic circuits. It is the only piezoelectric mineral of sufficient size and purity that is found abundantly in nature. Its extreme physical stability is reflected in the fact that there is practically no frequency drift even after long periods of use. It possesses superior elastic properties, which enable it to remain in sustained oscillation for long periods of time with no evidence of fatigue. Although brittle, its elasticity and physical strength permit it to be clamped securely between metal electrodes and to withstand minor shocks without chipping or breaking.

An idealized quartz crystal is a hexagonal prism, figure 1, terminated at each end in a pyramid. Natural crystals are found in an infinite

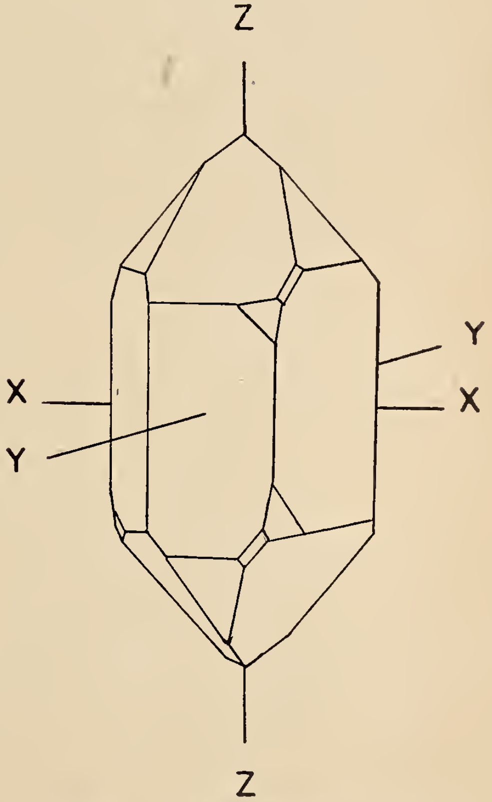

Figure 1. *An idealized quartz crystal.*

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[1] Electricity or electric polarity due to strain (that is, deformation of the crystal).

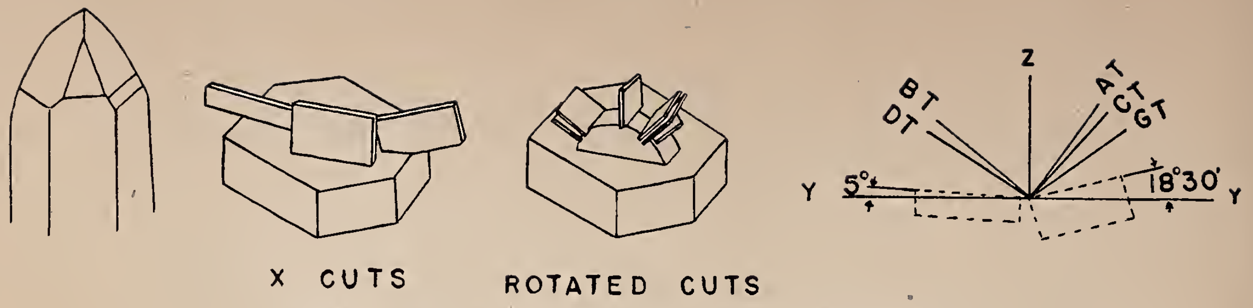

Figure 2. *Diagram showing orientation of various types of crystal cuts.*

variety of shapes and sizes, due to unequal growing conditions during formative periods and subsequent action of natural forces.

In this paper, as is customary among manufacturers of piezoelectric units, the axes of quartz shall be designated as the *Z*-, or optical, axis; the *Y*-, or mechanical, axis; and the *X*, or electrical, axis; as shown in figure 1. These axes, which are at right angles to each other, are important to crystal manufacturers because of the electrical and mechanical assymetry within the quartz crystal, which enables the manufacturer to cut crystals at specified orientations that will have advantageous properties, such as small frequency drift with varying temperatures and weak coupling to unwanted modes. A great many cuts of carefully specified orientation are secured from quartz (see fig. 2), and their characteristics and modes of vibration are determined largely by this orientation.[2]

II. Modes of Vibration

An understanding of the fundamentals of crystal grinding is contingent upon having an elementary conception of modes of motion in a quartz plate and their relation to its geometrical form. As with other elastic solids, the motion of the quartz bar or plate is largely determined by its dimensions, the type of wave excited, and the frequency applied. Only the modes of motion commonly associated with quartz plates will be considered here. They fall into three classifications: flexural, longitudinal, and shear.

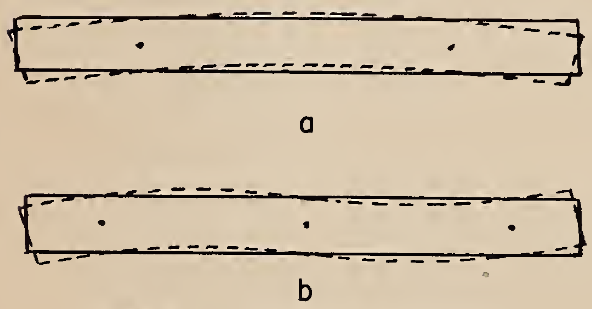

Figure 3. *Flexural motion in a quartz bar.*

The motion associated with the flexure is illustrated in figure 3, a and b, for the first and second orders. Dots in the illustrations represent nodes or points of little or no movement, and any clamping or supporting of a vibrating bar must be done at those points. For long, thin bars the frequency is dependent both on length and thickness, varying approximately with the square of the thickness and inversely with the square of the length. Crystals employing this flexural mode, such as the −5° cut, are useful in the frequency range below 50 kc, being the only cuts whose physical size remains small enough at those frequencies to make their use feasible.

If struck a sharp blow on one end in the direction of length, this same bar will be set into vibration in a longitudinal or extensional form of motion; in other words, it will increase and decrease in length at a frequency practically inversely proportional to the length and almost independent of the cross sectional area. In figure 4, a, solid lines represent the position of the bar before being struck, and outer broken lines show the bar in extension. The dot at the geometric center indicates the position of the node. A bar can also be induced to vibrate or oscillate in segments, as shown in figure 4, b and c, for second and third orders. The 18.5° bar employs the extensional mode and is useful in the frequency range from 50 to 200 kc.

When there is extension of a bar in one dimension, there is contraction in another. In other words, when a bar lengthens it becomes narrower, and when it shortens it becomes wider This lateral movement is practically negligible in a long thin bar, but it increases rapidly as width is increased and, in a square plate where width and length are equal, any increase in length about equals the decrease in width. A well-known crystal cut employing this type of motion is the GT, a rectangular plate with a width-to-length ratio of approximately 0.86 to 1, the width being the frequency-controlling dimension for the mode used.

The shear mode will be considered in two forms, the first of which, the face shear, can be described

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[2] A detailed treatment of the subject is given in reference [2].

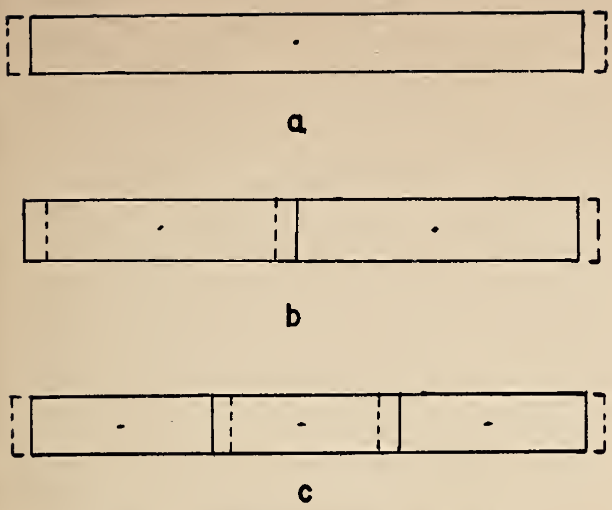

Figure 4. *Extensional motion in a quartz bar.*

as extension and contraction in opposite phase at right angles, or in a square plate, along the two diagonals, as illustrated in figure 5. It is difficult to show pictorially the face shear in higher order vibration because of the complicated nature of the movements. The nodal point is located at the intersection of the diagonals, and clamping must be at that point. Frequency is determined almost entirely by length and width. Thickness is not critical but must be adequate to provide the crystal with the necessary physical strength. Widely used cuts employing the face shear, known as *CT* and *DT*, are useful in the range from about 75 to 1,000 kc. These crystals are usually plated, and since the node is at the center they may be clamped or have wires soldered at that point.

In the high-frequency or thickness-shear mode these conditions are reversed, thickness being the frequency determining dimension, whereas length and width affect frequency but slightly. In this type of vibration, in the fundamental mode, one entire face, or the active part thereof, moves in one direction while the other moves in the opposite. The nodal position is not a point but a plane, parallel to and midway between the crystal faces. Due to boundary conditions, this shearing movement is most vigorous in the central area of the plate, diminishing until it becomes practically nonexistent near the edges. Consequently, pressure exerted at the corners does not damp the vibration, and corner clamping is used except in plated units in which wires support the crystal and also make electrical connection with the plating. Well-known thickness-shear cuts covering the range from 2 to 15 Mc and higher, are the *AT* and *BT*. Odd orders only of the thickness-shear mode can be excited, as illustrated in figure 6, a and b, for the first and third, respectively.

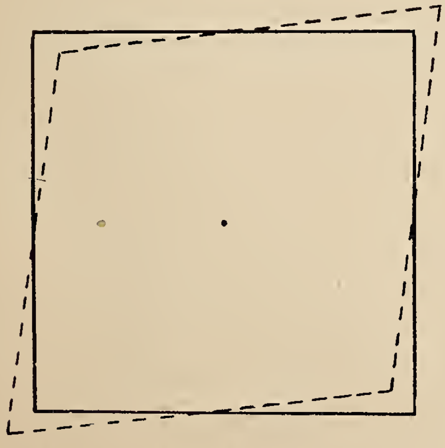

Figure 5. *Face-shear motion in a quartz plate.*

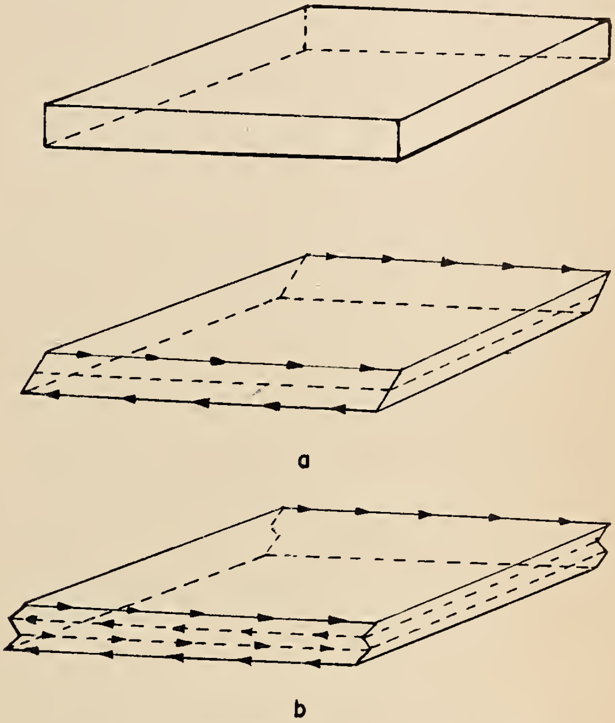

Figure 6. *Thickness-shear motion in a quartz plate.*

Thus far, a single mode of motion has been associated with a specific cut, but in actual performance it is usually coupled with other secondary modes. For example, in cuts most commonly used at high frequencies, the thickness shear is the desired mode, but low-frequency flexural and face-shear vibrations whose frequencies are determined by length and width dimensions are also present. If harmonics of these coincide with the high-frequency shear, they become extremely troublesome. For this reason precise dimensioning has become increasingly important in the manufacture of quartz oscillators. Unfortunately, temperature coefficients of these face shear and flexural modes are not the same as for the thickness shear. This accounts for the fact that a crystal may perform satisfactorily at one temperature and fail to do so at another only a few degrees removed. The carefully made *AT* or *BT* has a frequency that is far enough from harmonics of flexural or face-shear modes to permit wide variations in temperature before serious coupling effects appear.

Low-frequency *AT* crystals are more subject to interference from secondary modes because of the lower order of these modes and the closer coupling between them and the fundamental high-frequency shear. If the frequency change is large, several fluctuations may occur as the fundamental couples with successive interfering modes. As previously stated, these fluctuations are often accompanied by sudden jumps in frequency, which are extremely annoying because they often carry the frequency above the desired point. Since this tendency is present in all thickness-shear plates, although quite negligible in very thin crystals, an attempt will be made to give a simplified explanation of some of the factors involved.

Let us suppose that an *AT* crystal is to be brought to a frequency of 3,500 kc and that the dimensions are such that an overtone of a low-frequency mode has a frequency at, or very near, 3,500 kc. As the crystal is ground and fundamental shear approaches this frequency, the effects of coupling with the secondary overtone become apparent in the lessened activity[3] of the crystal and smaller frequency change with a given amount of etching or grinding. This latter effect is due to a mutual displacement that occurs when different modes approach and couple with one another, which causes the fundamental to level off along curve 1, as shown in figure 7, instead of following the broken line as it would if no interfering mode were present. When the thickness is such that the frequency in an uncoupled state would have reached *O*, the actual frequency may be at *C* or it may jump to *D* on curve 2. This dual frequency condition may extend a considerable distance on either side of *O*, starting, for example, at *AB* and ending at *EF*. It is obvious that the presence of the flexural overtone at 3,500 kc will make it impossible to bring the fundamental to that frequency. The remedy is to redimension the crystal so that the overtone will be raised to a new position where it will not interfere. It should be borne in mind, since these overtones are quite close together, that too large a change in dimension may merely move one overtone, for example the 34th, farther than is necessary and bring in the 32d which, if anything, will be more troublesome since it is of a lower order. The object is to find a dimension that will have no secondary flexural or face-shear overtones at 3,500 kc.

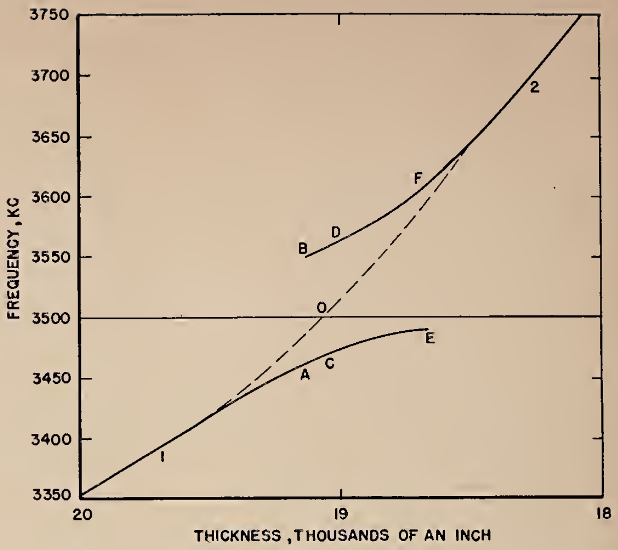

Figure 7. *Irregularity in the frequency versus thickness curve of an AT plate due to coupling with a low frequency harmonic.*

III. Zero Temperature Coefficient Cuts

Formerly, most crystals used in communications were *X* cuts, their faces normal to *X*, their edges parallel to *Y* and *Z*, and their frequency determined by an extensional mode in the *X*, or thickness direction. Due to defects inherent in the *X*-cut crystal, chief among which is its large negative temperature coefficient, it has been superceded largely by the zero temperature coefficient, high-frequency thickness-shear plates, which are known as the *AT* and *BT*. The term zero temperature coefficient as used here implies that the crystal frequency remains constant as the temperature changes. This, however, is true only for a small temperature range which, to be useful, must be at the operating temperature of the crystal, usually slightly above room temperature. For large temperature variations the crystal frequency follows approximately a square law curve as shown in figure 10. As is indicated, the crystal has a positive coefficient at low temperatures and negative at high. At the transition point, usually referred to as the turning point, and for several degrees on either side, the temperature-frequency coefficient is zero, or very small, and slight temperature variations will produce no appreciable frequency change. This position of the turning point can be predetermined by choosing the appropriate angle of cut.

The *AT*-cut with its major planes 35° 15′ off the *Z*-axis, has its turning point at approximately room temperature, a desirable feature since the temperature coefficient at that point is practically zero, and any small variation in room temperature will cause no appreciable frequency change.

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[3] The word "activity" is a somewhat ambiguous term used to indicate amplitude of oscillation.

Angles larger than 35° 15′ raise the turning point, and smaller angles lower it. The *BT*, with its major planes 49° on the opposite side of the *Z*-axis, also has its turning point at room temperature. Higher fundamental frequencies and greater stability may be achieved with the *BT*-cut, whereas the *AT* has higher activity, smaller temperature coefficient, and stronger overtone response.

IV. Redimensioning

Sometimes even a correctly oriented crystal will have an undesirable frequency-temperature characteristic, which will introduce frequency changes that are confined to a very narrow temperature range. If this temperature is the ambient temperature of a crystal that is being keyed, the resultant effect can be very annoying because it can cause a crystal to "chirp" from heat generated while in the oscillating period and subsequent cooling during the nonoscillating period. Improper dimensioning is frequently responsible for this behavior, although other factors, such as a wedge shape, or an uneven surface due to hand-grinding, may be the cause. In low-frequency *AT* plates, dimensioning must be done before final frequency is reached, because it often produces a several-hundred cycle increase in frequency. The same procedure should be followed in dimensioning all *AT* and *BT* plates, because even in thin high-frequency plates redimensioning may be accompanied by serious frequency changes.

Figures 8, 9, and 10 give the activity and frequency characteristics of the same 8,700-kc *BT*-cut crystal for three different dimensions. It was necessary to redimension twice before satisfactory performance was achieved. The redimensioning had no marked effect on the turning point, which is at approximately 30° C, except that in figure 8 the appearance of a coupled mode near the temperature of the turning point produced a distortion from the normal frequency curve represented in figure 10. In figure 9 the effect of interfering modes may also be noted, but the turning point remains unchanged.

If it is found desirable to raise the frequency of an oscillator by grinding or etching quartz from the major faces of the plate, it may also be necessary to change the edge dimensions in order to raise flexural and face-shear harmonics the same amount. This operation is one that requires extreme care because the amount of quartz that must be removed from the edges in order to main-

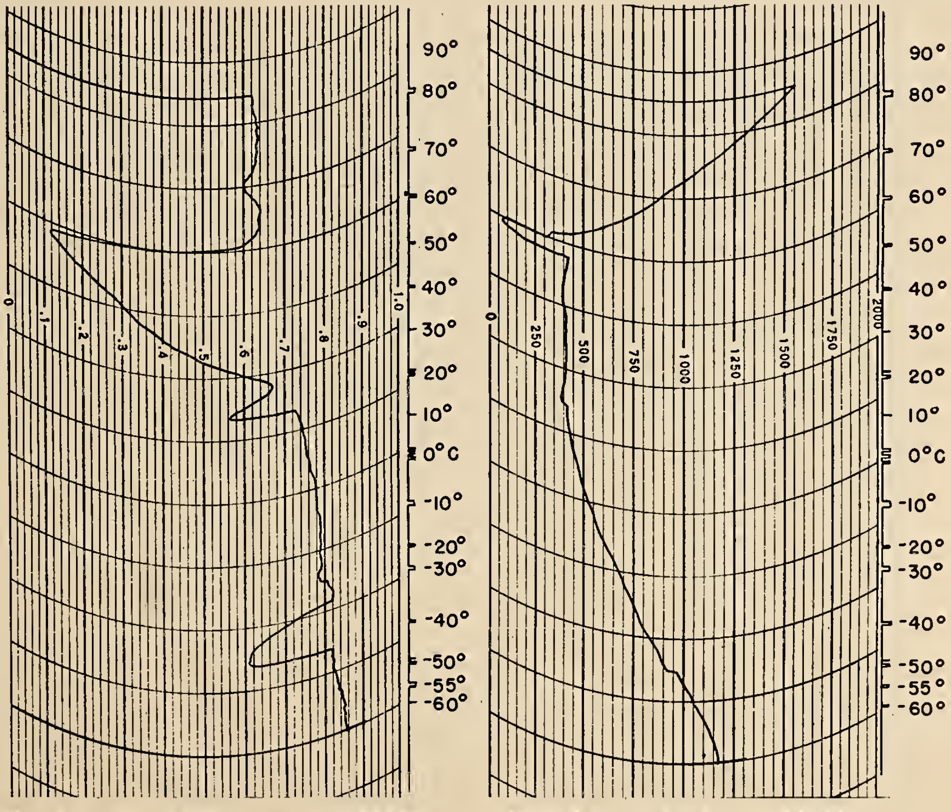

FIGURE 8. *Variations in activity and frequency of crystal No. 20 with temperature at the original dimensions.*

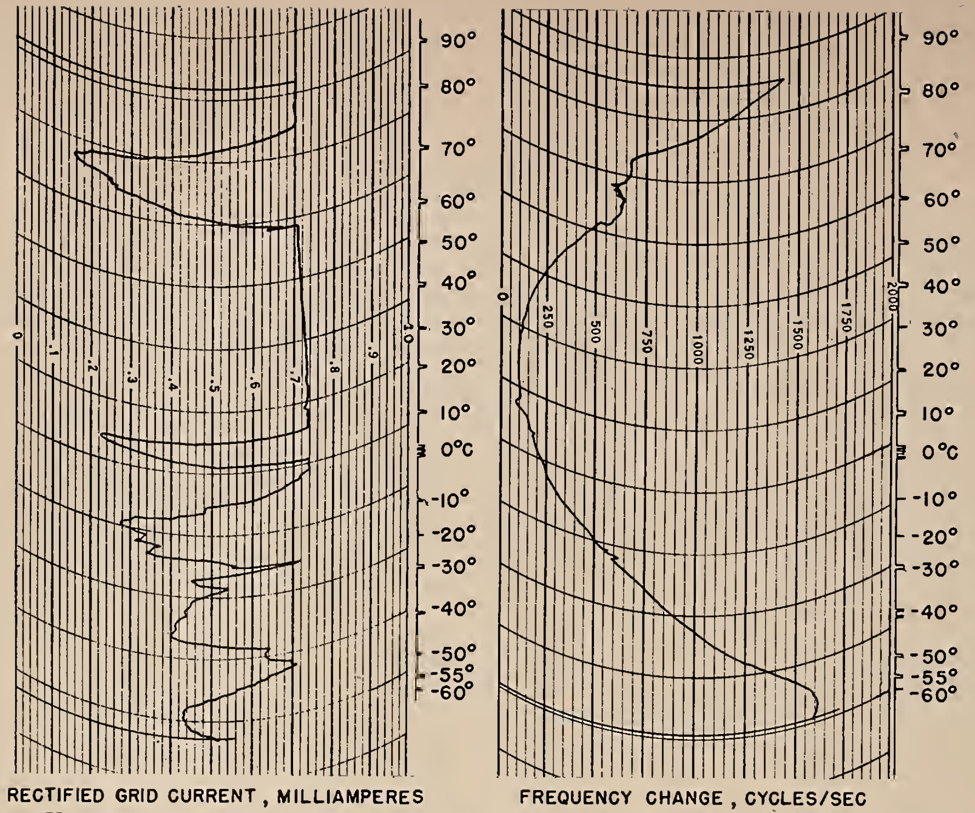

FIGURE 9. *Variations in activity and frequency of crystal No. 20 with temperature after the first redimensioning.*

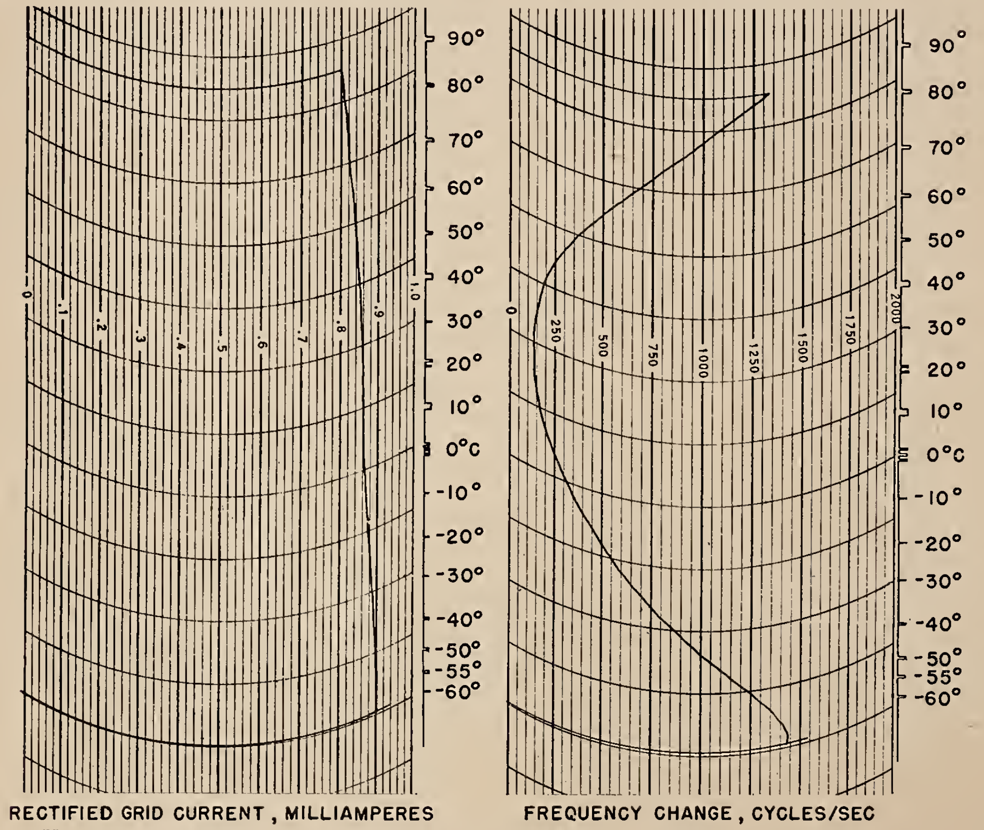

FIGURE 10. *Variations in activity and frequency of crystal No. 20 with temperature after the second redimensioning.*

tain the relationship is quite minute. The usual tendency of an inexperienced operator is to overshoot, bringing in overtones that previously were far enough below the fundamental frequency to cause no interference.

If the crystal performs satisfactorily after having its fundamental frequency increased a few kilocycles its edges need not be touched, but if erratic tendencies such as sudden fluctuations in activity or frequency develop, it is advisable to brush one pair of edges lightly on a glass plate charged with abrasive. If improvement is not evident, the same treatment should be given the other edges. This may be repeated several times, provided the amount removed each time is small. Failure of this procedure to change or improve activity, indicates that other factors may be responsible.

Such hit-or-miss dimensioning will of necessity be employed by the amateur grinder, since he will probably not have the essential dimensioning data available. Furthermore, it is questionable whether dimensioning data could be used if it were available, since length and width measurements of low-frequency plates are often invalid due to beveling, while those of high-frequency plates are difficult to secure because of the fragility of the crystal. A glass plate, to which a thin paste of aluminum oxide and water has been applied, may be used to grind the edges. The crystal may be held normal to the glass plate, thereby keeping edges perpendicular to the faces, or it may be held at an angle if a bevel is desired. A third method, very effective in making minor alterations, is to hold the crystal between thumb and forefinger and stroke the grinding plate lightly as a painter strokes a wall with his brush. Whether beveling should be employed depends mainly on the crystal frequency and the condition of the edges. Low-frequency plates are often beveled by the manufacturer, this being considered an effective method of improving activity and stability. Care should be taken to keep the edges parallel.

V. Frequency Adjusting

1. Etching

Frequency changes of the order of a few kilocycles can most satisfactorily be effected by etching quartz from the crystal surface. This is done by immersing in hydrofluoric acid or a water solution of certain fluorine compounds.[4] At the present time most crystals are finished by etching, because it is easily controlled, improves oscillator activity and stability, removes the aging [5] factor, eliminates hand-grinding, and permits more precise frequency adjustment. To achieve satisfactory results, crystals must be scrupulously clean, since the presence of oil and other impurities on the surface prevents uniform action of the etchant.

Crystal manufacturers now mechanically lap crystals to within a few kilocycles of the desired frequency, and finish by etching. Mechanical lapping gives to a crystal a symmetrical contour that cannot be duplicated by hand grinding. Immersion in an etchant does not change the contour if the crystal is clean. After an initial rapid change, time requirements must be determined by experimentation. The time-frequency relationship is fairly linear, except in certain low-frequency cuts where steps or rapid frequency changes may occur due to interfering modes. While it may be difficult to establish the maximum etching that may be done without adversely affecting crystal activity or stability, it is probably unwise to change frequency much more than 1 percent by this method. In any case, if the crystal loses activity and fails to respond to slight redimensioning, it is probable that the etching process has been carried too far.

2. Hand Grinding

For those who desire to change frequency beyond the limits attainable by etching, and for those who have no etching materials available, hand grinding is the established procedure.

In grinding a crystal, it is recommended that size 800 aluminum oxide or other fine abrasive be used. This should be placed on a flat piece of plate glass and moistened to form a very thin paste. If a large frequency change, which entails the removal of a great deal of quartz, is necessary, it is well to follow a routine procedure and employ a coarser abrasive, such as size 400 silicon carbide. The crystal should be rubbed lightly over the plate, with a figure eight or circular motion, holding the finger as nearly horizontal as practicable, and placing it at the center of the crystal, covering as much of the crystal area as possible. The same procedure should be repeated for three 90°-rotations of the crystal. Following this, the index and middle fingers should be placed on oppo-

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[4] A simple solution for etching quartz can be made by dissolving a rounded tablespoonful of ammonium bifluoride in a half pint of water and heating to a temperature of 60° C (140° F). A 7-Mc crystal, previously unetched, will have its frequency changed at a rate of slightly more than a kilocycle a minute, except that during the first 4 or 5 minutes the rate will be considerably faster, possibly 5 kc or more the first minute. Etching can be done at room temperature, but the action is very slow and a slight deposit is left on the crystal. Commercial quartz etchants are mixtures of fluorides and other chemicals. Other quartz etching solutions may be prepared by reference to the Chemical Formulary. Crystals to be etched should be placed in a wire rack and immersed in the etchant. Upon removal they should be washed thoroughly. All fluorine compounds are poisonous and the effects cumulative. Extreme care should be taken to avoid contact of the compound with the skin or inhalation of the vapors. Hydrofluoric acid, which is a water solution of hydrogen-fluoride gas, is so poisonous that it should never be used unless a fume hood is available.

[5] Aging is a slow upward frequency drift in a crystal oscillator. The most commonly advanced theory to explain aging is that small, sharp, so-called crystallites left on the surface by abrasive action tend to break off, thereby reducing mass and increasing frequency. Combined with this is a tendency for small fractures, produced by abrasion, to creep, thereby contributing to the aging process. Etching counteracts these aging factors by removing the crystallites and checking further fracturing.

site corners and the identical routine repeated. Pressure should at all times be kept light.

Following an established pattern such as that outlined above will enable the operator to keep the surface abrasion fairly uniform and thus prevent the formation of irregularities. Contour being probably the most important single feature of the *AT* or *BT* plate, any deviation from the ideal slightly convex surface contour has a detrimental effect on crystal behavior.

The inexperienced crystal grinder tends to exert a disproportionate amount of pressure at the center of the crystal. The resulting concavity contributes more towards loss of activity and erratic behavior than any other condition.

Another consequence of uneven finger pressure is production of wedge-shaped crystals, which are thicker at one corner or edge than at the opposite corner or edge. This introduces tendencies for crystals to jump from one frequency to another several hundred or thousands of cycles away, since there is a variation in thickness which, in *AT* or *BT* oscillators, is the frequency determining dimension. If the wedge gradient is too large, more than a few ten-thousandths of an inch in a half-inch square 7-megacycle crystal, the crystal ceases to oscillate because frequencies represented by various parts of the plate arc so widely separated that it is impossible for them to synchronize in a single operating frequency.

As previously mentioned, the type of contour most suitable for thickness-shear plates is one that is slightly convex, the degree of convexity varying inversely with the frequency, from about 0.0001 in. in a ½ by ½ in. 10-Mc plate to 0.001 in. in a 3-Mc plate.

If frequency changes involving removal of several thousandths of an inch of quartz are desired, a micrometer must be used to check contour so that it may be kept reasonably close to these specifications. Usual micrometer measurements fail to disclose certain irregularities that may be the cause of low activity and erratic behavior. Therefore, it is suggested that the micrometer be used as a deviation gage, by setting the jaws to fit the crystal loosely and sliding the crystal to and fro. In this way, extremely minute thickness variations may be readily detected. This is effective only if the crystal surface is absolutely clean, because particles of dust or abrasive may be mistaken for surface irregularities.

Even though contour is carefully controlled the crystal may still lose activity due to adverse coupling, which may be eliminated by redimensioning. If the crystal frequency is considerably below the final frequency, coupling with this same mode may occur again when the fundamental is further increased. Redimensioning only serves to change the frequency relationships in the crystal, and, as changing the fundamental thickness shear frequency does this, it is often unnecessary to do any redimensioning since it is quite possible that the final frequency may be favorably situated with respect to the interfering modes.

If it is suspected that some other factor may be responsible for the low activity, redimensioning may be used merely to help determine the cause. Should the activity not improve, the source of the trouble will probably be some defect in crystal symmetry that must be eliminated. In any case, redimensioning should be done sparingly.

As stated before, etching is the ideal method for adjustment of crystal frequencies, but hand grinding is the technique to be employed when large frequency changes are desired. Unfortunately, hand grinding introduces uncertainties that are related to the nature of the process and is usually accompanied by wide fluctuations in activity. As the fundamental is being increased, the coupling effects of the flexural and face-shear overtones are constantly changing and, simultaneously, minute contour modifications are being made. Therefore, fluctuations of one sort or another cannot definitely be attributed to any one factor. The question as to whether the change is due to interfering modes or to changes in contour always arises. Etching, by eliminating the possibility of a contour modification, also eliminates a good bit of the uncertainty because lowered activity may then be ascribed to adverse coupling effects, which may be removed by redimensioning. A logical place to start etching is at one of the points of high activity, provided the frequency is within etching distance of the desired frequency. In this way, the contour conditions which, in part, were responsible for this high activity, will be maintained.

3. Loading

Overshooting frequency, possibly the most annoying problem encountered in hand grinding crystals, need not be considered an irreparable misfortune, provided the degree of overshooting is not too great. Since a crystal is an elastic body oscillating at or very near its natural vibratory frequency, physically loading it with a suitable material will have a frequency lowering effect due to the fact that the mass of the oscillator is increased while the stiffness coefficient remains the same. Since loading of this type tends to lower activity, large frequency changes can be produced only in an oscillator of fairly high activity without seriously affecting the amplitude of oscillation. Changes up to 1 percent or more of the crystal frequency are possible.

The most important characteristic of the loading material is strength of adherence to the crystal. A satisfactory material that is readily available is solder. It may be rubbed into the crystal surface using light pressure. To be most effective, it should be applied equally to the central area of both faces. In order to estimate the amount required, the first application may be in the form of a circle approximately a quarter inch in diameter, which may serve as a boundary for additional loading. Again, work should be done in steps to avoid carrying it too far. In case an excessive load is added, part of it may be removed by rubbing with a soft eraser. If nitric acid is available, the entire load may be removed and the process repeated.

4. Cleaning

The last step in finishing (and a very important one) is thorough cleaning of the crystal, holder, and electrodes. A common cause of failure in oscillators is the presence of foreign matter such as dust or lint on crystal surfaces. Satisfactory cleaning agents are soap and water, carbon tetrachloride, trichlorethylene, or other grease-removing solvents. Forceps or tweezers should be used to immerse the crystal and associated parts in the solvent to prevent contamination of the solvent by oil from the fingers. The crystal should be dried with light pressure on a soft, clean, lintless cloth or towel. It is important to clean the crystal thoroughly each time it is to be placed in the holder to check frequency or activity. If the fingers are used to transfer it to the holder, only edges should be touched.

5. A Test Oscillator

Standard test oscillators were used by the military services during the war in order to secure correlated activity and frequency measurements from the various crystal manufacturers. Figure 11 is the schematic diagram of an oscillator circuit of the type that approximates the design of one of the most widely used in the frequency range from 0.5 to 30 Mc. The milliammeter, which measures rectified grid current, gives a reasonably accurate indication of crystal activity. The capacity of 25 $\mu\mu$f in the grid circuit, plus the interelectrode and stray capacitance, all of which totals about 32 $\mu\mu$f, represent the load into which the crystal works. Variations in this load capacitance produce changes in the rectified grid current as well as in the frequency. Increasing the load capacitance has the effect of decreasing both the activity and frequency. If values indicated in the circuit diagram are used, a crystal unit should produce a grid current of 0.4 ma or better. Plate tank components have a lesser effect on crystal activity in this circuit, except that a larger inductance to capacitance ratio produces more grid current. Care should be taken to limit rectified grid current to about 1 ma to prevent damage to the crystal. This may be done by lowering the oscillator supply voltage.

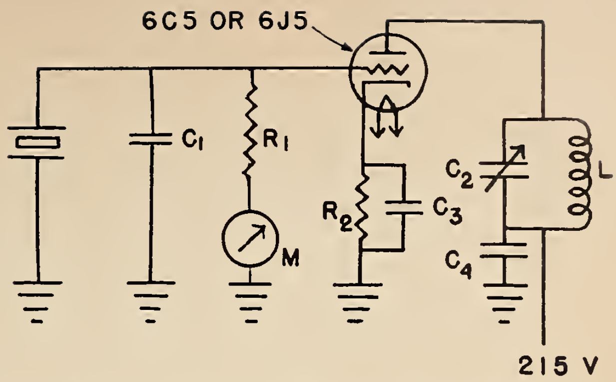

FIGURE 11. *Circuit diagram for a crystal test oscillator.*

C_1=25$\mu\mu$f; C_2=20 to 140 $\mu\mu$f; C_3, C_4=0.01 μf; R_1=100,000 ohms; R_2=300 ohms; M=0–1 d-c milliameter; L=15 turns No. 18 wire 1½-in.-long by 1½-in.-diameter form.

This oscillator should be used as an activity comparator, absolute reading being of secondary importance for many applications. Before beginning operations on a given crystal its activity should be checked, and thereafter the oscillator constants should not be changed. Minor fluctuations in activity are unavoidable, but any large decrease may be an indication that undesirable contour conditions are being introduced. Skillful use of the micrometer will usually disclose whether a low center, uneven corners, or some other factor, or combination of factors is responsible. There is the possibility, especially in low-frequency crystals, that loss in activity may be caused by coupling with low-frequency modes, in which case increasing the frequency by further removal of quartz will lessen the coupling and restore activity.

Hand-finishing of crystals is an art. Directions given here are to be regarded as a starting point for the novice who may make modifications to suit his own particular case. Experience is the best teacher, and the individual will do well to keep a record of his observations and thus acquire a fund of empirical data that may be of considerable value.

VI. References

[1] W. G. Cady, Piezoelectricity (McGraw-Hill Book Co., Inc., New York, N. Y., 1946).

[2] R. A. Heising, Quartz crystals for electrical circuits (D. Van Nostrand Co., Inc., New York, N. Y., 1946).

[3] F. R. Lack, Observations on modes of vibration and temperature-coefficients of quartz crystal plates, Bell System Tech. J. 8, 515 (1929).

[4] F. R. Lack, G. W. Willard, and I. E. Fair, Some improvements in quartz crystal circuit units, Bell System Tech. J. **13,** 453 (1934).

[5] W. P. Mason, Electrical wave filters employing quartz crystals as elements, Bell. System Tech. J. **13,** 405 (1934).

[6] P. Vigoureux, Quartz oscillators and their applications (His Majesty's Stationery Office, London, 1939).

[7] R. B. Wright and D. M. Stuart, Some experimental studies of the vibrations of quartz plates, J. Research NBS **7,** 519 (1931) RP 356.

WASHINGTON, March 14, 1949.

U. S. GOVERNMENT PRINTING OFFICE: 1949