CHAPTER XIV

Effects of Manufacturing Deviations on Crystal Units for Filters

By A. R. D'HEEDENE

14.1 THE EFFECT OF DEVIATIONS IN THE CHARACTERISTICS OF CRYSTAL UNITS ON FILTER PERFORMANCE

THIS chapter emphasizes primarily the need for close control in the manufacture of crystal units for use in filters. The first telephone use of crystal units in the commercial manufacture of filters was made by the Western Electric Company in about 1936. To make such commercial manufacture practical, it was necessary to establish accurate design information and allowable manufacturing tolerances. The quantitative data collected for this purpose provided the chief source of material for this chapter. While the data is quite extensive, it will be observed that there are still some factors which must be treated qualitatively.

While filter crystal units are like oscillator crystal units in that they must have low internal dissipation and a close control of resonant frequency, they are different in that many additional characteristics of the filter crystal units must also be controlled accurately. Two typical illustrations will demonstrate how characteristics other than resonant frequency and Q may react on filter performance.

The first characteristic considered is the slope of the reactance with frequency curve in the vicinity of the series resonant frequency. This slope is sometimes referred to as the impedance level of the crystal unit. A convenient measure is the inductance of the equivalent electrical circuit. When this inductance departs from its nominal value, the performance of the filter using the crystal unit may undergo appreciable change. This is particularly true of filters in which the schematic contains a lattice or some other type of bridge circuit with crystal units contained in all the bridge arms. For example, in Fig. 14.1 the solid curve illustrates the transmission characteristic obtained from a lattice-type crystal filter, in which both the series branches and the diagonal branches contain two balanced crystal units. High loss results from a close impedance balance between the branches of the lattice. When the inductance of any of the crystal units departs from its nominal value, the bridge balance is disturbed and the transmission characteristic of the filter is changed. The two dotted curves of Fig. 14.1 illustrate the characteristics that result when the inductance values of the crystal units in either branch depart from their nominal values by about one per cent. A negative departure in one branch results in about the same effect on performance as a positive departure in the other branch. The two curves shown on Fig. 14.1 differ in that one assumes a positive departure and the other a negative departure for the inductance of a branch.

Due to the close impedance balance which is required for these filters, the effect of small departures in resonant frequency will produce rather large variations in the transmission characteristic. For example, departures of about 10 cycles per second in the crystal units of either branch will produce variations in discrimination of about the same type and magnitude as those illustrated in Fig. 14.1 for departures in inductance. On the other hand, if the crystal units of both branches exhibit equal departures the entire

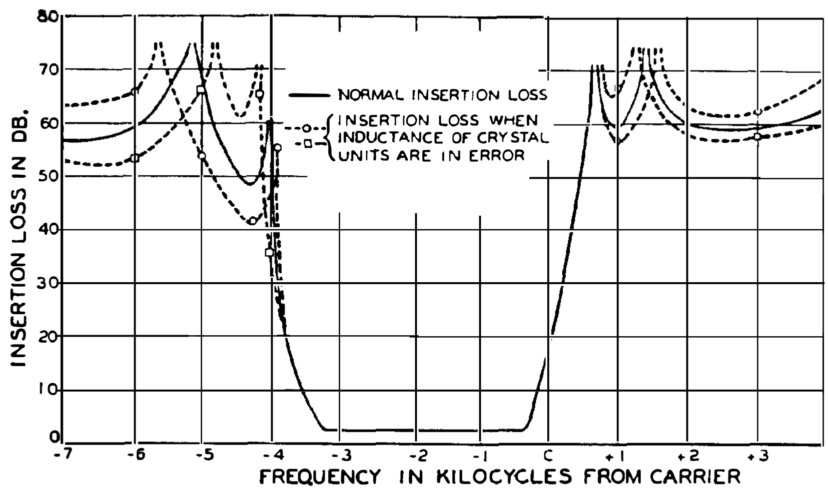


Fig. 14.1.—The insertion loss characteristic of a crystal band-pass filter as affected by deviations in the inductance of the crystal units.

transmission characteristic will be shifted by the frequency departure of the crystal units, and there will be no loss in discrimination.

Another way in which deviations in the properties of crystal units may react on filter performance is illustrated by the schematic and curves shown in Fig. 14.2. The schematic is the equivalent electrical circuit of a narrow band filter, using two balanced quartz crystal units. The filter is designed to provide a passed band of about 10 cycles per second with distortion of less than 0.2 db. The insertion loss characteristics show that the desired transmission can be obtained for various magnitudes of effective resistance as long as the resistances in the series and diagonal branches are equal. However, if the effective resistance in one branch is twice as large as that in the other branch a highly distorted characteristic results as shown by the middle curve of Fig. 14.2.

Both of these illustrations show that filter performance is degraded rapidly if the crystal units of the lattice have characteristics which depart from their nominal values by different extents for the two branches. A similar effect is produced when the temperature coefficient of resonant frequency for the crystal units in one branch differs from the temperature coefficient of the units in the other branch. Deviations occurring in a single unit may also affect filter performance. Such deviations include the presence of unwanted resonances of even weak amplitude, inadequate insulation resistance between the metallized coatings or unbalance between the halves of plates on which the coating has been divided.

The importance of controlling the electrical characteristics of the crystal units is indicated from the above considerations. It is pertinent to correlate deviations in the mechanical properties of the crystal unit with the devia-

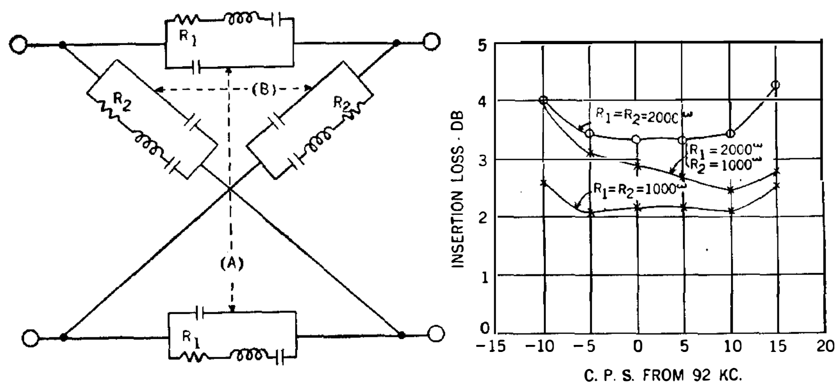


Fig. 14.2.—Effect of deviation in the effective resistance of crystal units on the distortion characteristic of a crystal filter.

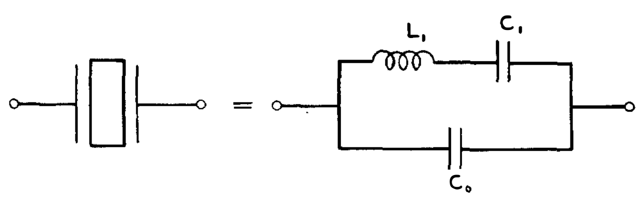
tions in electrical characteristics. This is the subject of the succeeding sections. Consideration is restricted to the plates commonly used in filters, that is, X-cut plates, vibrating in extensional or flexural modes, and GT-cut plates.

14.2 The Effect of Deviations That Occur in the Manufacture of Quartz Plates

Quartz is an anisotropic material. Accordingly, plates cut from a quartz crystal exhibit elastic and piezo-electric properties which depend on the orientation of the plates with respect to the principal axes of the crystal. For that reason, any deviation in the orientation of the plates from nominal will affect the electrical characteristics of the crystal units. In addition, these characteristics are affected by imperfections in the plates due to deviations in linear dimensions, to the presence of flaws, or to the condition of the surface of the plates. The effects of these deviations differ for various cuts of crystal plates, for plates of various shapes and for the various modes of vibration. In the following paragraphs, each type of deviation will be considered in turn and data will be presented to show its effect on the characteristics of crystal units using the various types of plates.

14.21 Deviations in the Angle of Orientation

Accurate information is available on the effect of deviation in angle of orientation on the characteristics of X-cut plates vibrating in the extensional mode. The relation between the electrical characteristics of this type of vibration and the properties of the quartz are shown in Fig. 14.3. This information, with minor changes, is reproduced from a preceding publication.[1] In Fig. 14.3: *l*,*w* and *t* are the length, width and thickness respectively of the plate; *K* is the dielectric constant; ρ is the density;



$$C_0 = \frac{K\,w\,l}{4\pi t} \times \frac{1}{9\times 10^{11}} \quad \text{FARADS} \qquad f_R = \frac{1}{2\,l\sqrt{\rho\, s'_{22}}} \quad \text{CYCLES PER SECOND}$$

$$L_1 = \frac{\rho\, s'^{2}_{22}\, t\, l}{8\, d'^{2}_{12}\, w} \times 9\times 10^{11} \quad \text{HENRIES} \qquad C_1 = \frac{8\, d'^{2}_{12}\, w\, l}{\pi^2\, s'_{22}\, t} \times \frac{1}{9\times 10^{11}} \quad \text{FARADS}$$

Fig. 14.3.—Equivalent electrical circuit of piezoelectric crystal.

d'_{12} is the piezo-electric constant; and s'_{22} is the modulus of compliance (inverse of Young's modulus). All these quantities are expressed in c.g.s. electrostatic units. The quantities which depend on the orientation of the plates are the piezo-electric constant and the modulus of compliance. The symbols for these quantities usually are primed when they are used for a generalized orientation. When unprimed, the symbols designate quantities measured along the principal axes. For X-cut plates, deviations of the plane of the major surface from the YZ plane have relatively small effect, while variations in the angle of rotation about the X-axis have a relatively large effect on these quantities.

Mason has shown[2] how the magnitudes of the piezo-electric constants

[1] "Electrical Wave Filters Employing Crystals with Normal and Divided Electrodes", W. P. Mason and R. A. Sykes, *B. S. T. J.*, April 1940, p. 222.
[2] "Electrical Wave Filters Employing Quartz Crystals as Elements", W. P. Mason, *B. S. T. J.*, July 1934, equations on page 451; also in Chapter VI.

and the moduli of compliance for any angle of rotation may be derived from their magnitudes along the principal axes of quartz. Using these equations and the magnitudes for the principal axes tabulated in Chapter I by Mason, d'_{12} and s'_{22} have been calculated as a function of the angle of rotation of the plates about the X-axis. In turn, the frequency and inductance constants have been calculated as a function of the angle of rotation, using the relations shown in Fig. 14.3. Figure 14.4 is a plot of the frequency and inductance constants as a function of the angle of rotation for angles between about $-70°$ and $+70°$. It shows how the inductance and resonant frequency of these plates will change with deviations in the angle of rotation. The frequency constant used is the product of the resonant frequency in kilocycles and the length of the plate in millimeters. The inductance

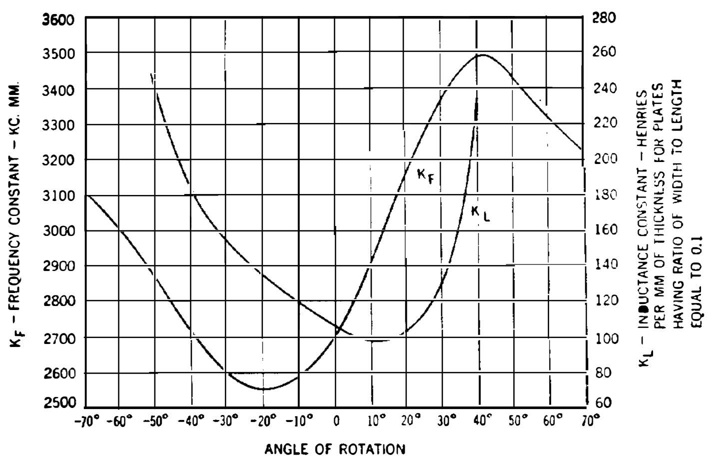


Fig. 14.4.—Frequency and inductance constants of X-cut quartz plates as a function of their angle of rotation around the X-axis.

constant used is the inductance per millimeter of thickness of a plate having a width-to-length ratio equal to 0.1.

The change of inductance and resonant frequency with deviations in angle of rotation about the X-axis is of particular interest for the angles of rotation most commonly used, that is for $-18.5°$ and for $+5°$. The calculations indicate that for an X-cut plate rotated $-18.5°$, a deviation of $\pm 1°$ in the angle of rotation will change the inductance by $\mp 1.2\%$ respectively, and the resonant frequency by $+.05\%$ and $-.02\%$, respectively. For an X-cut plate rotated $+5°$, a deviation of $\pm 1°$ will change the inductance -0.6%, and $+0.9\%$, respectively, and the resonant frequency by $\pm 0.7\%$.

Deviations in angle of rotation will, in general, affect temperature coefficient. The effect is illustrated by Fig. 1.19 of Chapter I, which, for X-cut plates, shows the relation between temperature coefficient and angle of rotation. The curve shows that the temperature coefficient is practically zero for an angle of rotation of $+5°$. For that reason this particular cut is used whenever a low-temperature coefficient is desired. The curve also shows that at this point the slope of temperature coefficient as a function of angle of rotation is zero. Hence, for the $+5°$ X-cut plate, which is most important from the standpoint of temperature coefficient, there will be little change due to a deviation in the angle of rotation.

In GT-cut plates the effect of deviation in the angle of orientation must be considered in combination with deviations in linear dimensions. Mason shows[3] that for an angle of rotation of $+51$ degrees 7.5 minutes and a width-to-length ratio of .859, a temperature coefficient close to zero may be obtained from $-25°$ C to $+75°$ C. He also has shown that this temperature coefficient varies with both the angle of rotation and the width-to-length ratio. Because of this, it has been found possible to compensate for small deviations in the angle of rotation by adjusting the linear dimensions. The net effect of a deviation in angle of rotation, after it has been so compensated, is to raise (or lower) the temperature region of zero temperature coefficient by 11° C for each 10-minute increase (or decrease) in angle of rotation. In GT-cut plates, the width dimension directly controls the primary resonance. For this reason, it is preferable to adjust temperature coefficient by varying the length dimension rather than the width. The crystal plates are cut larger than desired. The frequency of resonance and the temperature coefficient are then adjusted simultaneously by grinding either the width or length dimension as required. Experimental work carried on by L. F. Willey of the Laboratories shows that an increase of 1.0 per cent in the width-to-length ratio results in an increase in temperature coefficient of approximately $+1.35$ parts per million per degree C. In his experimental work Willey used the ratio of the secondary to the primary frequency as a convenient measure of the width-to-length ratio. The inductance constant for GT plates, which is about 17 henries per millimeter of thickness, will increase by less than 1% for deviations in any of the angles of rotation of as much as 30 minutes. However, the inductance may depart appreciably from nominal due to the adjustment of width and length dimensions.

14.22 Deviations in Linear Dimensions

In the case of X-cut plates, the length dimension is used to control the location of their resonant frequency. The length is lapped to its final dimen-

[3] "New Quartz-Crystal Plate, GT, Produces Constant Frequency Over Wide Temperature Range", W. P. Mason, *Proc. I. R. E.*, May, 1940, p. 220.

sion after all other processes have been completed, so that this dimension will be such as to compensate for the effect of any other deviations that may have occurred. The sensitivity of this adjustment depends on the mode of vibration. For plates vibrating in their extensional mode, the resonant frequency is inversely proportional to the length, as shown in Fig. 14.3, while for plates vibrating in their flexural mode, the resonant frequency is inversely proportional to the square of the length. The amount of the adjustment required depends on the magnitude of the frequency errors that may have been introduced due to deviations in the width or in the angular orientation of the plates or due to still other causes. The magnitude of such frequency errors, in turn, depends to a considerable degree on the angle of rotation of the plates. For example, it was shown in Section 14.21 that a deviation in the angle of rotation of a $+5°$ plate changes its resonant frequency more than ten times as much as a similar deviation in a $-18.5°$ plate. It must be noted that the adjustment of length compensates for frequency errors only and that errors in inductance or temperature coefficient may be increased by such adjustment.

Deviations in the thickness dimension principally affect the impedance level of the plates. As shown by Fig. 14.3, the inductance is directly and the capacity inversely proportional to the thickness. In the case of GT-cut plates the thickness dimension is important also because it controls the location of the most prominent unwanted resonances, which arise from vibrations in thickness flexure. However, plates are designed to avoid critical thicknesses and small deviations from the nominal thickness will not usually result in plates having unwanted resonances.

Deviations in the width dimension affect the equivalent electrical characteristics appreciably. The effect of deviations in width on the frequency of X-cut plates vibrating in their extensional mode can be deduced from the curves of Fig. 14.5. The curves show that this effect is more pronounced for larger values of the width-to-length ratio where coupling with the width extensional mode becomes appreciable. For a $-18.5°$ plate with a width-to-length ratio of 0.8 an increase of 1% in the width dimension will decrease the frequency by about .04%. For a $+5°$ plate with a width-to-length ratio of 0.4 an increase of 1% in the width dimension will also decrease the frequency by about .04%, but for a ratio of 0.6 the decrease in frequency will amount to 0.13%.

Similar information is available for crystals vibrating in width flexure from the measurements published by Harrison[4] and the calculations published by Mason.[5] This information shows that for small ratios of axes

[4] "Piezo-Electric Resonance and Oscillatory Phenomena with Flexural Vibration in Quartz Plates", J. R. Harrison, *Proc. I. R. E.*, Dec., 1927.

[5] "Motion of a Bar Vibrating in Flexure Including the Effects of Rotary and Lateral Inertia", W. P. Mason, *Jour. Acous. Soc. America*, April, 1935, pp. 246–249.

the resonant frequency will be directly proportional to the width dimension. However, as the ratio is increased to 0.5, a change of 1% in the width dimension will change the frequency by only 0.5%.

The effect of the width dimension on the inductance of the plates frequently is important. Fig. 14.6 illustrates the relation between inductance and the ratio of axes. From these curves the effects of deviations in width can be deduced. For the two longitudinal plates, the inductance is almost inversely proportional to width. For the flexure plate, the decrease of inductance with increase in width is much more rapid. With a ratio of

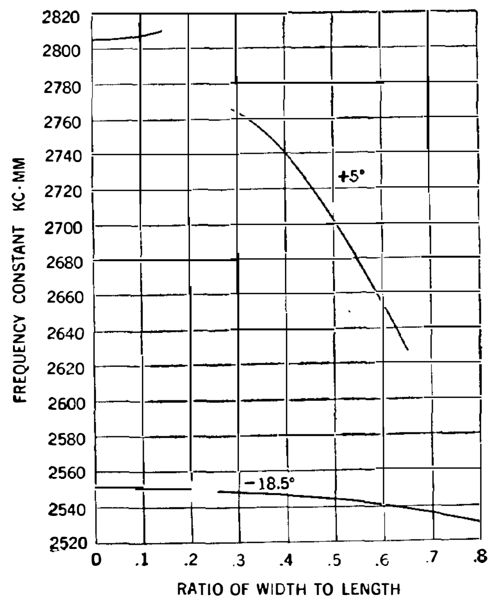


Fig. 14.5.—Frequency constant of the longitudinal mode of X-cut quartz plates as a function of their ratio of width to length.

axes of 0.6 the inductance decreases about as a square power, while with a ratio of 0.1 the decrease is about as the third power.

The width dimension of the +5° plate has an appreciable effect on the temperature coefficient of the plate. Mason has shown that while the temperature coefficient is zero for a long narrow bar, it increases quite rapidly as the width dimension increases, due to coupling between the face shear and the longitudinal modes. In the case of an −18.5° plate, coupling with other modes is relatively weak. Hence its temperature coefficient, which is about 25 parts per million per degree C, does not change appreciably with changes in width. For a +5° plate vibrating in its flexure mode, Fig. 14.7 illustrates measurements made on the variation of temperature coefficient with ratio of axes. For all these X-cut crystals, it may be observed that deviations of 1% in the width dimension will not change the temperature coefficient by more than 5%. Such changes are usually negligible.

14.23 Internal Defects

Internal defects in the quartz plates may have a large effect on their electrical characteristics. These defects vary so widely in type, size and

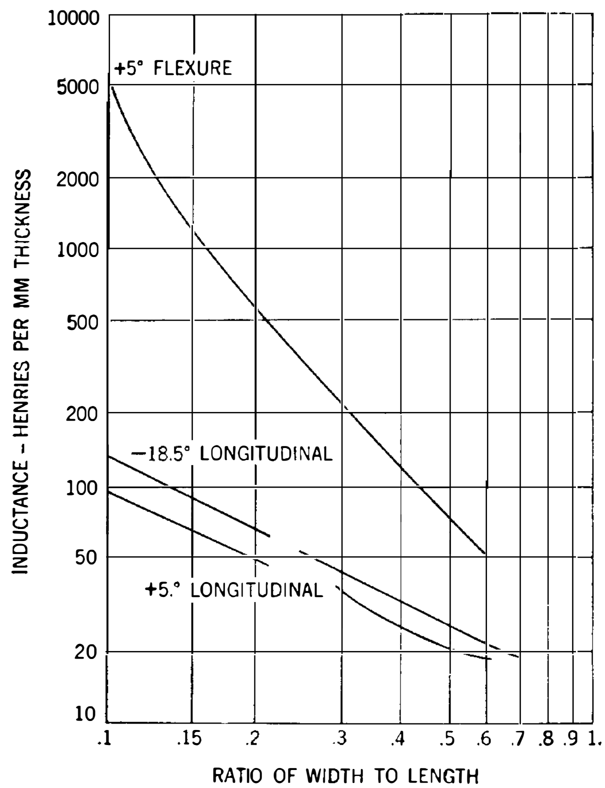


Fig. 14.6.—Inductance of the crystal units used in filters as a function of the cuts of the plates and their ratio of width to length.

concentration that it is impossible to predict the effects quantitatively. General comments regarding the results that may be expected for various defects are described in Chapter IV. The conclusions drawn there for oscillator plates are also applicable to filter plates. These are: (1) evidence that a particular defect is permissible in a given type of plate does not prove that a similar defect is permissible in some other type of plate, and (2) proof that a particular defect is permissible in a given type of plate can be obtained only by a statistical study.

Some qualitative statements can be made regarding the effect of mechanical flaws. Cracks result in instability of resonant frequency and effective resistance and must be avoided. The effect of inclusions or chips depends on the size of these defects relative to the size of the finished plates and also on their location in the plate.

Twinning in quartz may be either of the optical type (Brazil twin) or of the electrical type (Dauphiné twin)[6]. The effect of these two types of twinning on the performance of oscillator crystal units has been described thoroughly in Chapter V.

When optical twinning is present, the plate will exhibit the same elastic properties throughout, but the two portions of the plate will tend to expand

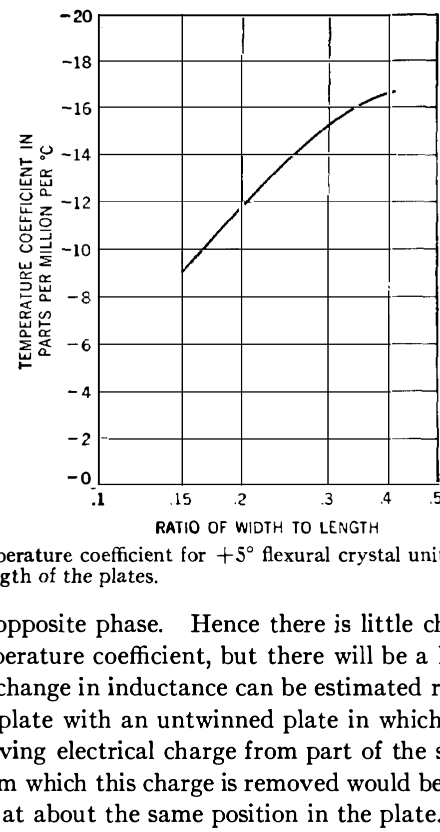


Fig. 14.7.—Temperature coefficient for +5° flexural crystal units as a function of the ratio of width to length of the plates.

and contract in opposite phase. Hence there is little change in frequency constant or temperature coefficient, but there will be a large change in inductance. The change in inductance can be estimated roughly by comparing the twinned plate with an untwinned plate in which activity has been reduced by removing electrical charge from part of the surface. The area of the surface from which this charge is removed would be twice the twinned area and located at about the same position in the plate.

It is believed that a small amount of electrical twinning is more serious than a similar amount of optical twinning, because the twinned areas are of opposite angular sense. Each of the two areas has a different modulus

[6] "The Properties of Silica", R. B. Sosman, Chapter XII.

of compliance and the effective modulus of the plate has a value intermediate between the two different values of moduli. Therefore, the frequency constant of the plate will be intermediate between that of the desired cut and its electrical twin. For a small amount of twinning, the direction and rate of change of frequency can be estimated from the comparison shown on Table I between the standard filter cuts and their electrical twins.

This verifies the experimentally observed fact that for $-18.5°$ X-cut plates, twinning increases the frequency, while for $+5°$ X-cut and GT plates, twinning decreases the frequency. Even for small amounts of twinning the inductance will increase rapidly for plates of any orientation. When the amount of twinning becomes large, the equivalent inductance approaches infinity. That is, the crystal will not be set in motion by an applied voltage.

The quantitative effect of twinning (probably electrical) has been measured on one set of plates by R. M. Jensen. Figure 14.8 includes a photograph of the plates used, illustrating the extent of the twinning in each. All of the plates are $-18.5°$ X-cut plates, having the dimensions 30.88 x 10.56 x .86 mm. The tabulation below the photograph compares

TABLE I

Filter Plate	Frequency Constant—kc. m.m.	Electrical Twin	Frequency Constant—kc. m.m.
$-18.5°$	2560	$+18.5°$	3120
$+5°$	2815	$-5°$	2650
$+51.1°$ (GT)	3280	$-51.1°$	2610

the inductance and resonant frequency measured for each of the plates with the one, designated AN-3, which shows the least effect of twinning. While there is a good correlation between the amount of twinning in the plates and their change in electrical performances, it is not practical to estimate accurately the effect of a given amount of twinning. For this reason, crystal plates having any twinning should not be used for crystal units for filters.

14.24 Etching

The surface condition of the quartz plates also has some effect on crystal characteristics. This surface condition is determined in large part by the lapping operation used to obtain final dimensions. As described in Chapter XIII, the plates are given a final lap with 400 or 600-mesh carborundum. This, in turn, is followed by an etching bath which removes foreign particles. A short etch, about eight minutes in 47% hydrofluoric acid, has been found adequate to ensure firm adherence of the metal coating to the quartz. On the other hand, the use of a relatively long etch, 30 minutes or more, is desirable when a high Q is desired. The long etch also results in an improved stability of the resonant frequency as a function of current. This will be discussed in a subsequent paragraph. A disadvantage of a long etch is the difficulty of controlling the etching process within close toler-

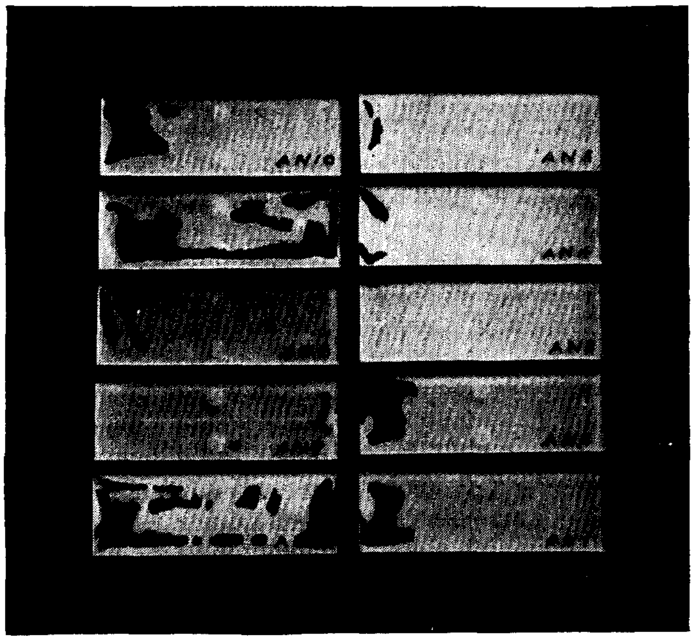


Plate Designation	Percentage Increase over Values Measured for AN-3: Inductance	Resonant Frequency
AN-1	+22.12	+.50
AN-2	+27.20	+.59
AN-3	0	0
AN-4	+3.03	+.04
AN-5	+3.12	+.01
AN-6	+276.54	+5.01
AN-7	+1.58	−.03
AN-8	+14.21	+.37
AN-9	+738.00	+6.63
AN-10	+32.44	+.83

Fig. 14.8.—Effect of various degrees of twinning on the performance of −18.5° X-cut quartz crystal plates.

ances. The variations in rate of removing material may be sufficient to affect the uniformity of the linear dimensions of the plates.

These factors indicate that etching is an important process in preparing crystal plates. A close control must be maintained on the strength of the acid, the uniformity with which the surfaces of the plates are exposed and the duration of the exposure.

14.3 The Effects of Deviations during Fabrication of Wire-Supported Unit

As described in Chapter XIII, two types of mountings have been developed for supporting crystal plates, the Pressure Type and the Wire-Supported Type. The wire-supported type of mounting is the more recent development and has resulted in crystal units which have a much higher degree of stability and can be reproduced within much closer tolerances than the units using the pressure type of mounting. Since this chapter is concerned chiefly with the problem of obtaining a high degree of precision in crystal units, the discussion is restricted to the wire-supported type of mounting.

14.31 Silver Spotting

For the wire-supported type of mounting the first operation is to bake small silver spots on the surface of the crystal plates. In the application of these silver spots to the crystal plates three factors are of importance in their effect on the characteristics of the plate, namely, the size of the spot, its location, and the firing temperature. Since in all crystal designs to date the silver spots are applied at or near the nodal line of the crystal plate the principal effect of the spots is to increase the stiffness of the plate, so slightly increasing the frequency of resonance. Variations of an appreciable magnitude in either the amount of silver paste used (that is, the size of the spot) or in the location of the spot with respect to the nodal line will change the resonant frequency of the plate. Such changes could be corrected later, when the plates are adjusted for resonant frequency, as long as the length is increased sufficiently to allow such adjustment. However, if the length be increased sufficiently to allow for extreme cases, average adjusting time will be increased materially, while if the allowance is insufficient some of the plates may be unusable. For this reason, close control of the size and location of the silver spots is well justified.

In baking the silver spots, care must be taken to prevent "heat" twinning If the temperature of a quartz plate is raised above the inversion point (573°C) and then is reduced again, the plate will be electrically twinned. The firing temperature of the silver paste currently used for the spots is not many degrees below this inversion point. Hence, the firing temperature may easily become so high as to result in twinned plates. In addition, it has been observed that the twinning may occur at a considerably lower temperature if the plate is subjected to large thermal stress. For this reason, care must be taken to heat the plates uniformly during the baking operation.

14.32 Division of Coating

The next operation is to evaporate a coating of silver on the surface of the quartz plates. The plates must be thoroughly cleaned before this coating is applied in order to ensure firm adherence of the coating. Poor adherence may cause the coating to peel off the plate, changing all of the electrical characteristics of the plate.

In many cases the coating must also be divided.[1,7] Two methods are in general use for dividing the silver coating on crystal plates, namely, an abrasive method and an electrical stylus method. In general, the abrasive method of dividing the coating is superior to the electric stylus for all cases requiring a simple straight line division, but it has not been found practical for complicated divisions such as are desirable for harmonic longitudinal plates and flexure plates.

In using the abrasive method for dividing the coating only two factors are likely to change the characteristics of the crystal plate, these being the location and the width of the dividing line. Deviations in the location of the dividing line from the lengthwise center line for a longitudinal plate will affect the capacity and inductance balance between the two halves of the plate. Deviations in the width of a properly centered dividing line will cause changes in the inductance of the plate since for a given plate the inductance is a function of the ratio of the plated area to the total area of the plate. So, for a wide crystal plate deviations in the width of the dividing line will be negligible while for narrow plates these deviations can cause an appreciable change in the inductance of the plates.

When the electric stylus is used for dividing the coating, the location and the width of the dividing line again will affect the performance of the plates. In addition, varying amounts of twinning will occur along the division line apparently due to instantaneous high temperature gradients introduced by burning of the silver at the point of contact of the stylus. In measurements made on a group of $-18.5°$ X-cut crystals on which the coating has been divided carefully with an electric stylus, the increase in the inductance of the plates ranged from 1.4% to 2.6%. Any twinning resulting from the dividing operation will also change the resonant frequency of the plates.

14.33 Soldering of Wires to Plates

The next process, that of soldering the supporting wires to the crystal plate may have considerable effect on the performance of the unit. The

[1] Loc. cit.
[7] "Crystal Channel Filters for the Cable Carrier System", C. E. Lane, *B. S. T. J.*, January 1938, pp. 125–136.

deviations which may be introduced depend on the amount of solder used, the location of the solder button with respect to the nodal line of the plate, the shape of the solder button, and the possible twinning of the plate during the soldering operation.

The amount of solder used in forming the joint of the wire to the plate becomes extremely important when the plate is small. For example, Fig. 14.9 illustrates the changes in the frequency-temperature characteristic resulting from the use of varying amounts of solder for a particular size of plate. The units on which these measurements were made used X-cut +5° plates of 16 mm x 6 mm x 0.5 mm. The types of wire referred to in the figure, that is, hooked, straight and headed, were described in Chapter

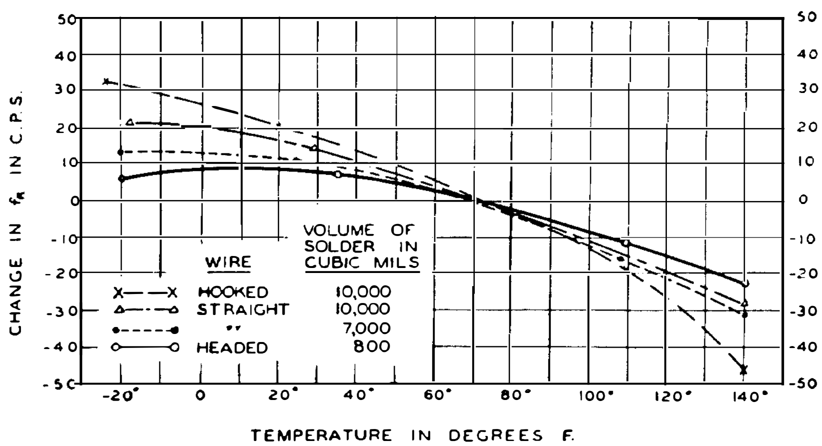


Fig. 14.9.—Change of resonant frequency with temperature of +5° X-cut quartz crystal plates. The curves show that when the volume of solder used for joining the plates to the supporting wires is appreciable compared to the volume of the plates, the frequency-temperature coefficient characteristic is affected by the volume of solder.

XIII. The frequency-temperature characteristic expected on the basis of measurements made on crystal units using larger plates is approximated closely by the solid curve. This solid curve actually was obtained from measurements made on crystal units using plates supported with headed wires and using a very small amount of solder. The other curves show that the temperature coefficient will be increased appreciably due to the presence of a larger amount of solder. Further, when the larger amounts of solder are used, the characteristics depend on the exact amount of the solder, so that the characteristics represented by the dashed curves are hard to reproduce.

The amount of solder used in this operation also affects the Q of the crystal unit and its resonant frequency. Measurements using several crystal plates of relatively small sizes have shown improvements in Q of as much as 25 per cent when headed wires are used over that obtained with other wires using larger amounts of solder.

Variations in the consistency of the solder joint will, of course, affect the adherence of the supporting wire to the plate. A poor joint will result in a high effective resistance for the crystal unit and will generally cause instability both in resistance and in resonance frequency.

In soldering the supporting wire to the crystal plate two methods have been used for melting the solder; namely, the soldering iron, and the hot-air blast. With either method, lack of sufficient control can seriously change the electrical characteristics of the plate due to twinning. It has been observed that this twinning occurs when there is a large temperature gradient in the quartz, even at temperatures well below the inversion point. Experimental work by G. W. Willard has indicated that it may occur even when the temperature of the soldering iron is as low as 300°C. To avoid such twinning during the soldering operation, it has been found desirable to raise the temperature of the entire plate to just below the melting point of the solder.

Twinning, when it occurs, will affect the crystal plate by causing an increase in inductance, a change in the resonant frequency, increased effective resistance, and a change in the temperature coefficient, as stated previously. Also, in crystals with divided plating there will be an inductance unbalance between the two halves of the crystal plate set up due to unequal amounts of twinning. Several measurements made, using GT plates at 160 kc, showed that twinning during the soldering operation decreased the resonant frequency in a range from 200 to 100 cps and the temperature coefficient of the units ranged from 2 to 6 times that of units using untwinned crystal plates.

14.34 Effects due to Wire Resonance

As described in Chapter VIII, the characteristics of crystal units may be changed due to vibrations set up in the supporting wires. When any one of the wires is not located exactly on a node of the plate, the plate will set the wire into vibration. For certain critical lengths of the wire, it will offer considerable resistance to this motion and there will be a rapid increase in effective resistance and some change in resonant frequency of the crystal plate.

The effect of wire vibration can be described in terms of its electrical analogy. The vibrating wire, clamped at its far end, may be considered a rather special electrical transmission line open-circuited at its far end. When viewed from the crystal plate the impedance changes rapidly with frequency in a succession of pronounced resonances and anti-resonances. In the vicinity of an anti-resonance the electrical equivalent of the vibrating wire may be approximated by a coil and condenser in parallel as shown by L_2 and C_2 of Fig. 14.10. This acts in series with the mechanical resonance of the quartz plate, represented by L_1 and C_1. The impedance curves illustrate the effect of the wire resonance on the crystal impedance. R_1, the equivalent resistance of the crystal plate, is constant for frequencies in the vicinity of resonance. X_1, the equivalent reactance of the crystal plate, increases rapidly as the frequency departs from resonance. R_2 and X_2, the equivalent resistance and reactance of the wire resonance, are typical of an anti-resonant electrical network. The curve labeled $(X_1 + X_2)$ shows the

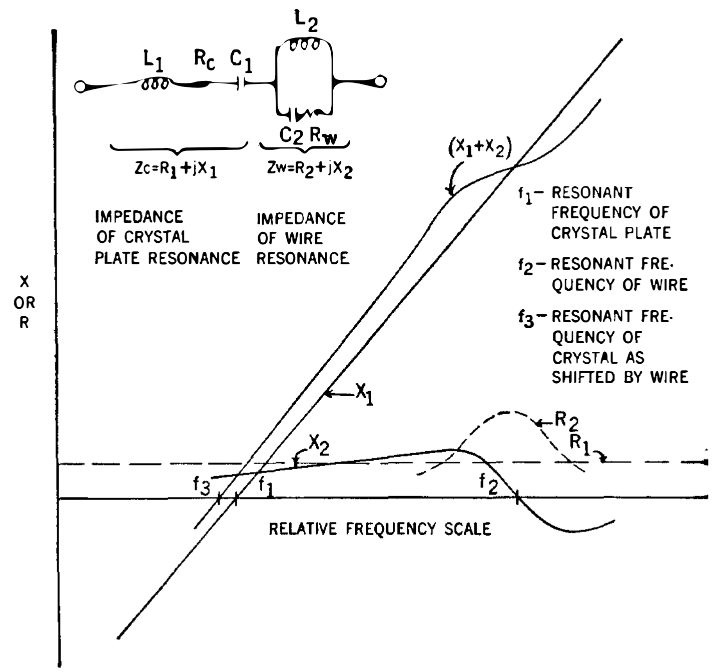


Fig. 14.10.—Effect of wire resonance on the resonant frequency of a crystal unit.

effect of the wire resonance on the response of the crystal plate. It may be observed that the apparent resonance has been reduced by a small frequency decrement. The amount of frequency shift and the increase in effective resistance depend on the Q of the wire resonance, its frequency location compared with the resonance of the crystal plate, the mass of the wire relative to that of the quartz plate, and the distance from the node to the point at which the wire is actually fastened to the plate.

The slope of the frequency-reactance characteristic corresponding to the mechanical resonance of the quartz plate is very steep and the effect of the wire resonance will be noticed only when an anti-resonant frequency of the wire is close to the resonant frequency of the plate. The changes in resonant frequency and effective resistance due to wire resonance have been measured for some filter crystal units and the measurements are tabulated in Table II.

The relation between the length of a wire and the frequencies at which it will resonate in flexural modes is expressed by the following equation:

$$l = m \sqrt{\frac{vd}{8\pi f}}$$

where v is the velocity of sound in the wire
- d is the diameter of the wire
- l is the length of the wire
- f is the frequency of wire resonance in cycles per second
- m is any one of a series of numbers representing the zeros or poles of the impedance of the vibrating wire. A different series is obtained for each assumption regarding the restraints on the ends of the wire.

TABLE II

EFFECT OF WIRE VIBRATIONS ON THE RESISTANCE OF A QUARTZ CRYSTAL PLATE

Crystal Type	Mode of Vibration for Crystal	Resonant Frequency	Crystal Mass in Grams	Distance of Wire from Nodal Line	Maximum Frequency Shift CPS	Maximum Increase in Resistance
+5° X-Cut	Flexural	12 kc	.51	(M) .060″	±2.0	250%
+5° X-Cut	Longitudinal	164 kc	.142	(N) .012″	±30	640%
−18° X-Cut	Longitudinal	335 kc	.075	(M) .002″	±90	360%
−18° X-Cut	Longitudinal	552 kc	.068	(N) 0.0″	±75	1100%
5th Harmonic GT	Longitudinal	164 kc	.98	(M) .011″	±12	370%

(N) Specified Dimension.
(M) Measured Dimension.

At a particular frequency and for wire of a particular material and diameter there is a series of critical wire lengths which must be avoided. The critical lengths are those which cause the wire to present a high impedance to the motion of the plate. This high impedance may be considered, from the electrical point of view, as corresponding to an anti-resonance of the wire. The critical lengths are defined by the series of numbers $m \doteq (n + \frac{1}{2})\pi$ where n takes the values 1, 2, 3, etc. This series applies to a wire which is clamped at the far end and, while free to vibrate at the driving end, is constrained to a slope perpendicular to the plate.

If it be assumed that the wire is free to bend at the driving end, the critical lengths are those corresponding to the series of numbers $m \doteq (n + \frac{1}{4})\pi$, as compared with $m \doteq (n + \frac{1}{2})\pi$ for the constrained case. Measurements indicate that the actual critical lengths lie somewhere between the lengths obtained from the two assumptions. The reason that the restraints are not exactly of one type or another is probably due to the use of solder at both ends of the wire.

While a wire could be designed to have a minimum impedance at the resonant frequency of the crystal, this is relatively unimportant. As a matter of fact, since the wire is of relatively low characteristic impedance a small departure from the critical length is sufficient to avoid trouble from wire resonance. In order to allow for as wide a manufacturing tolerance as possible the supporting wire is usually designed to have a length half-way between two successive critical lengths. For a 6.3-mil phosphor-bronze wire, the spacing between successive critical lengths ranges from about 58 mils at 100 kc to about 15 mils at 1000 kc. Hence, even at 100 kc the length of the supporting wire must be controlled within a tolerance of about 20 mils.

These supporting wires are formed to have definite bends along their length and the location of these bends varies slightly from one wire to another. In addition, the wires are terminated by solder at both ends. Because of these complications it is impractical to meet such close tolerances on the effective length of the wires. Furthermore, a wire that does have a suitable effective length at room temperatures may exhibit sufficient change of properties with variations in temperature so that it becomes of critical length at some other operating temperature.

Much of the difficulty due to wire resonance is avoided by use of a solder ball on the supporting wire, as described in Chapters VIII and XIII. The solder ball is located near the quartz plate. Since it serves as a clamp at that point, it makes the supporting wire short. By locating and forming the solder ball accurately, the length of the supporting wire is controlled within a close tolerance. Further, since the wire is shortened by use of the ball it is less affected by changes in temperature. Experience at about 500 kc indicates that a tolerance of about 10 mils in locating the solder ball is practical and has provided satisfactory operation between $-40°C$ and $+85°C$.

14.4 Need For Cleanliness and Low Relative Humidity

One of the most serious difficulties encountered in manufacturing quartz crystal plates is that of assuring sufficient cleanliness. Even minute particles of foreign matter will introduce appreciable changes in crystal performance.

Usually, the presence of foreign matter will act to load the crystal and will reduce the resonant frequency but there are also instances where the added matter tends to stiffen the plate and increase its frequency. The latter has been observed to occur as the result of the deposit of a thin film of rosin on the surface of the plate. In the presence of foreign matter on the surface of the plates, the performance will be unstable with time and temperature even after the plate is sealed into a container. Also, erratic variations are observed as the plate is shifted from a normal atmosphere to a container which is evacuated or filled with dry air. Experience has shown that elaborate precautions for insuring cleanliness are justified by the time saved in the adjusting processes.

The need for cleanliness is closely related to the effect of humidity on the insulation resistance of crystal units. As used in filters, crystal units must provide extremely high impedances at their anti-resonant frequencies. These impedances may be as high as 100 megohms. With clean crystal plates in relatively dry atmospheres, such insulation resistance can be maintained up to 1000 kc. However, even a trace of salts or other types of contamination will make the insulation resistance highly sensitive to moisture in the adjacent air. While it is relatively difficult to measure insulation resistance at high carrier frequencies, the effect of the reduced insulation

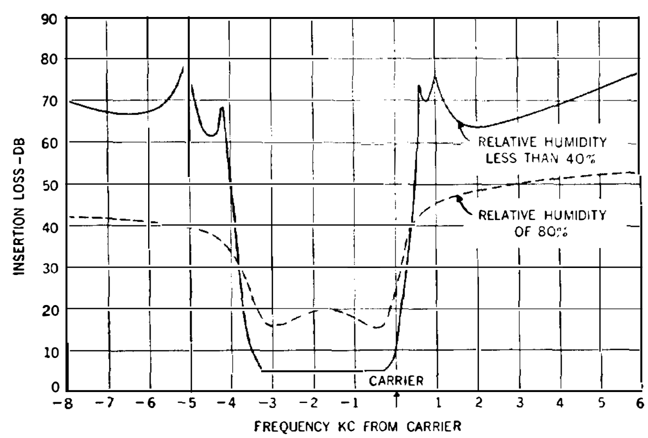


Fig. 14.11.—Effect of humidity on the discrimination of channel crystal filters. To prevent decrease of discrimination with increase of relative humidity, the crystal units must be hermetically sealed.

due to moisture is evident on inspection of the discrimination characteristics of the filters. For example, Fig. 14.11 illustrates the result of high relative humidity on the transmission characteristic of a typical crystal filter. It may be observed that the discrimination almost disappears for a relative humidity of 80%. These measurements were made on a filter containing well cleaned crystal plates. It will be found frequently that an unsatisfactory discrimination characteristic is produced by considerably lower values of relative humidity when the plates are not so clean. Experience has shown that it is impractical to let the relative humidity surrounding the crystal plate exceed 40% for satisfactory filter performance. When a high degree of accuracy is required, the plates are assembled in a unit which is either evacuated or filled with air at a relative humidity of less than 5%.

14.5 Effect of Current Level

Crystal units will undergo change in effective resistance and in frequency of resonance as the current transmitted is increased. Some change might be expected due to the heating of the plate by the dissipative loss associated with the transmission of current. However, the effects are not identical with those obtained with a change in ambient temperature. Appreciable changes have been observed even when using GT-cut plates adjusted to zero temperature coefficient as shown, for example, in the curves of Fig. 14.12. Also, it has been observed that after a plate has been driven hard and the

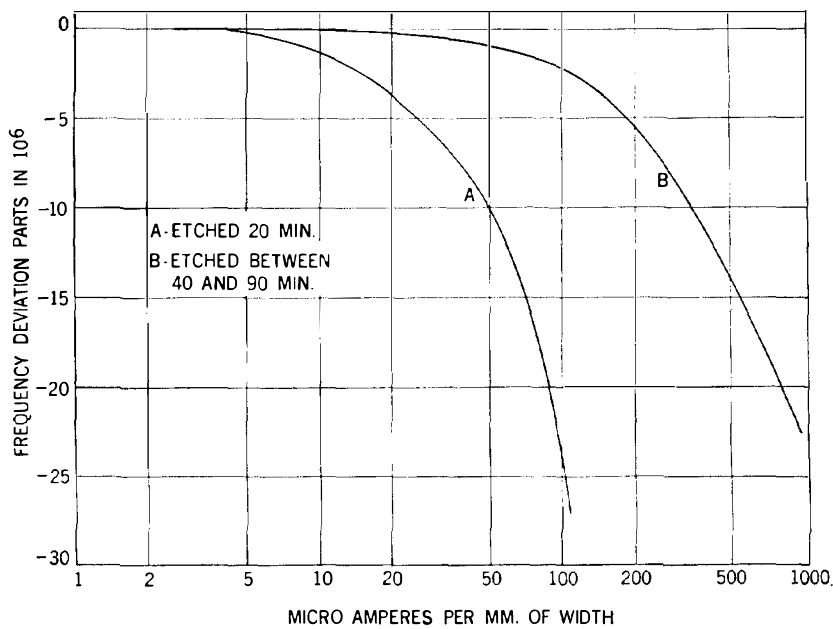


Fig. 14.12.—Change of resonant frequency of GT-cut plates due to increase of transmitted current.

transmitted current then reduced, the original resonant frequency is restored only after a considerable time interval. The data of Fig. 14.12 provides a rough correlation between stability and current levels. For example, if the stability desired for a crystal unit using a GT type plate be in the order of one part per million, the circuit design should be such as to keep the current level in the plate below about 10 microamperes per millimeter of width.

The parameter used in these paragraphs for measuring current levels is the current per unit of width. This appears to be useful as a common basis for comparing various plates of any one cut and mode of vibration. Theoretically, in the case of a plate vibrating longitudinally, the current, I, per unit of width, w, is directly proportional to the elongation per unit of length, y_v, as shown by following equation:

$$I/w = K\,y_v$$

where K is a constant which depends on the cut of plate and mode.

Figure 14.12 also illustrates the importance of the surface condition of the plates. Curve A is the average frequency-current characteristic for a group of crystal units using plates etched for twenty minutes in 47% hydrofluoric acid and curve B the average characteristic for a group of crystal units using plates etched for over forty minutes but less than ninety minutes. While the data is incomplete, it provides some evidence that crystal units using plates which have been etched for a long period exhibit a frequency-current characteristic which is appreciably more constant than those using plates etched for a shorter period.