CHAPTER VIII

Principles of Mounting Quartz Plates

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Introduction

IT IS the object of this chapter to show some of the fundamental considerations involved that govern the design of mountings or holders of quartz crystals. This discussion is restricted to the three common types, namely, rod or clamp type, wire type and airgap type. The development of these three types of mountings for applications in telephone transmission and radio systems has led to many and varied forms. Commercial designs of units for telephone uses employing these principles are described in detail in a later chapter.

In chapter VI regarding the vibrations of crystals we have assumed in all cases that the crystal is free to vibrate. In order that this condition shall be fulfilled it is necessary that any mounting which supports the crystal shall not restrict its vibration or at most the effect shall be made as negligible as possible.

8.1 Clamp Type Supports

Of the known types of vibration it is noticed in all cases that there have been nodal points. These points by definition are points of zero motion and in all cases that we have studied appear to be single isolated points or lines of very small size in comparison with the total crystal area. The obvious type of mounting is then one which simply clamps the crystal with a very small area at these points or nodes. The early type of mountings for low-frequency crystals were all based on this principle and the area of the clamp was determined experimentally by reducing it until, with sufficient pressure to hold the crystal, a good Q was obtained. The first mountings consisted simply of two pressure points located as nearly as possible to the nodal point. It was apparent at first that this type of mounting allowed the crystal to rotate about the mounting axis and very shortly the plating or electrode open-circuited. With the development of the "-18 degree X-cut" crystal it was found that the nodal region of a longitudinally vibrating crystal was a nodal line and permitted the use of a knife-edged type of mounting instead of the single point. This type of pressure mounting was used with this crystal for quite a number of years in the crystal filters for carrier systems and is shown in Fig. 8.1. This consists mainly of four pressure edges whose dimensions along the length of the crystal are small and width sufficiently large to insure a rigid clamp. Pressure was applied by a phosphor bronze spring in the center of the two top pressure points. This gave a satisfactory mounting and also allowed the use of a divided plating necessary for the balanced type crystal filters. This type of mounting was used in crystals of relatively low frequency, for example, 60 to 150 kc. of the "−18 degree X-cut" type.

With the use of higher-frequency crystals of different types of vibration than that described above, it has been found that this method of mounting has not been very satisfactory. In order to reduce the size of the mounting in proportion to the decreased crystal area it would be a delicate mechanical job and quite costly. This type of mounting could not be used for crystals which did not employ this type of vibration, for example the face shear type such as the *CT* and *DT*, since there is only one spot near the center which would permit clamping at all.

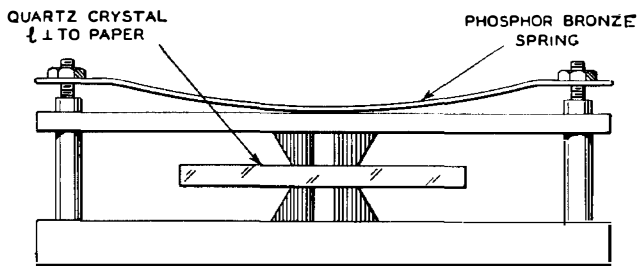

Fig. 8.1—Pressure mounting for extensional crystals.

To permit a crystal to vibrate freely the object used to support the crystal and maintain contact to the plated surfaces must have a very low mechanical impedance. At the same time it should possess sufficient rigidity that the complete assembly may be shocked without changing characteristics of the crystal as an oscillator. For example, if a rod or bar is held against a crystal at any point we would expect that the crystal in an oscillating condition would tend to generate motion in the bar and as this bar is placed closer to the nodal point we would expect the motion to be less. It can be seen that there are two objects to be accomplished in mounting a crystal: First, that the support must be placed as close as possible to a nodal point; and second, that the support shall have a very low mechanical impedance. This mechanical impedance needs to be low only at or near the operating frequency of the crystal. One type of support which would meet this requirement is that of a rod in flexure a discussion of which is given in Chapter VI. In this case, however, we may clamp one end of the bar and allow the other end to be free to vibrate. This free end would then be in contact with the surface of the crystal. If the bar were clamped and were of a length such that its frequency of resonance equalled that of the crystal or approximately so, it would require very little energy from the crystal to drive it, and any energy received from the crystal would be reflected from the clamped end of the bar and thereby kept within the vibrating system. This type of support is shown in Fig. 8.2, where l = length of the rod and d its diameter. The slightly rounded end is to allow the rod to seat firmly on the crystal surface. An enlarged view of Fig. 8.2 is shown in Fig. 8.3 and shows how the rod would vibrate. Figure 8.3A shows the type of motion for the first mode of a clamp-free bar. Figure 8.3B shows the type of motion of the same bar vibrating

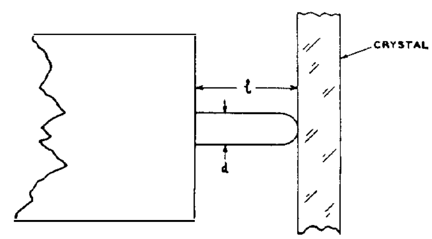

Fig. 8.2—Cantilever type mounting.

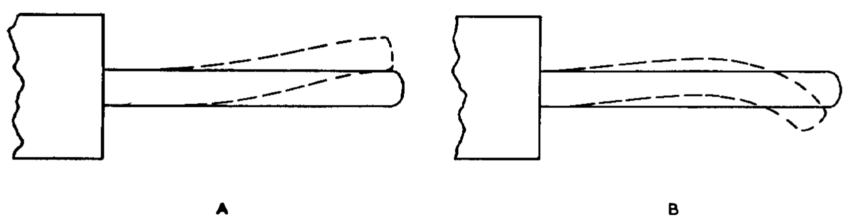

Fig. 8.3—Type of motion in cantilever support mountings.

in its second mode. This would indicate that for a given length of bar we could use it at several different frequencies by simply using higher orders of vibration. By using a clamp type mounting where the clamping rods are designed as shown in Fig. 8.2, we may now have a mounting which at the crystal frequency will allow the crystal to vibrate unrestricted but at the same time provide a very secure clamp thus preventing the crystal from moving about in its holder. To prevent rotation of the crystal about the axis of the clamped points, more than two can be used provided they are of the proper design. The frequency of a clamp-free rod in flexure is given by equation (8.1) where m now has values different than in the case of free-free flexure.

$$f = \frac{m^2 dv}{8\pi l^2} \tag{8.1}$$

where v = velocity in cm./sec.
d = diameter in cm.
l = length in cm.
m = 1.875 for first mode
= $(n-1/2)\pi$ for 2nd, 3rd, etc.

From this we can compute the length necessary for a given rod at a given frequency and use this for the design of the clamping rods. This length is given in equation (8.2) for the case of a 100-kc crystal using phosphor bronze rods 1 millimeter in diameter

$$\begin{aligned} l &= 1.875 \sqrt{\frac{.1 \times 3.6 \times 10^5}{8\pi \times 10^5}} \\ &= .225 \text{ cm} \end{aligned} \tag{8.2}$$

This corresponds to the case of Fig. 8.3A. For the case of Fig. 8.3B, the length is given by

$$l = .567 \text{ cm}$$

Using this same diameter rod, if we should go to a considerably higher frequency, for example 5 megacycles, the value of l would be extremely small even for the case of Fig. 8.3A and would be somewhat smaller than the diameter of the rod. As mentioned before in Chapter VI, the simple formulae that apply in the case of flexure are only for the case of a long thin rod. When the length becomes equal to or less than this diameter, it is very probable that the support member should be designed as though it were vibrating in shear. These follow well-known rules and are only mentioned here in case designs for high-frequency crystals are contemplated using this method.

The design of rod-supported crystals following this procedure has not been carried on to a large extent in these laboratories because, at present, the wire-supported crystal appears to have many advantages. A great deal more of the work in regard to resonating supports has been done for the case of the soldered lead type[1].

8.2 Wire Type Supports

The theory of resonating supports involving soldered leads on crystals is very similar to that just discussed for the case of rods. There are two additional elements that we have here that are not present in the case of the rod, these elements being the actual solder connections that fasten the wire

[1] The presence of standing waves on the lead wires of CT crystals was found experimentally by Mr. I. E. Fair.

to the crystal and the coupling between the crystal and wire vibrating systems. Considerable work has been done in regard to the amount of solder necessary and the most desirable shape for the solder cone. The complete assembly of a wire support for a crystal is shown in Fig. 8.4. The shape of the solder cone shown in Fig. 8.4 has proved to be the most desirable and has been termed as "bell-shaped." This type of cone formation allows the wire to be twisted in handling and still not break away the top of the cone and form an appreciable crater. For the purposes of analysis we may then assume that the cone becomes part of the crystal and moves with it so that when computing the length of a wire vibrating in flexure, this length should be determined from the top of the cone. The amount of solder used in the cone since it is part of the crystal must be kept at a minimum in order that the constants of the crystal equivalent circuit will not be modified too much by it. One established fact of the effect of the solder in the cone on the

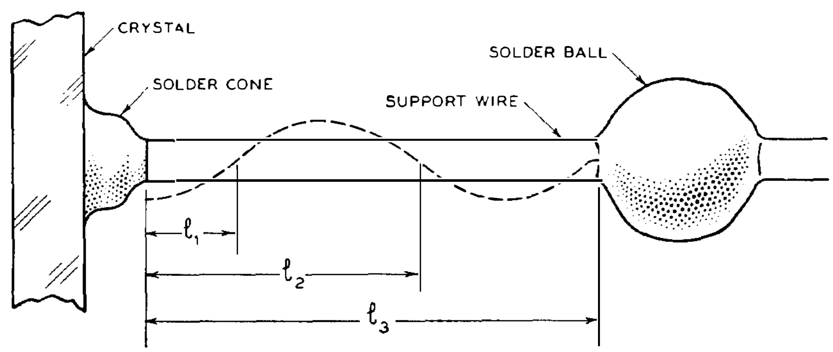

Fig. 8.4—Soldered lead type mounting.

equivalent circuit is to raise the resistance in the equivalent circuit for the crystal and this resistance increases considerably with an increase in temperature. The amount of solder permissible in the cone would then be determined by the maximum temperature at which the crystal is to be operated and the minimum Q allowable. The type of motion that the crystal would generate in the support wire when oscillating is that shown in Fig. 8.4 by the dotted line. The solder ball shown to the right of the figure acts as the clamp for the wire. This solder ball may be placed at any point along the wire corresponding to a node. The diameter of this ball need only be sufficient to act as a clamp. In general, this will be in proportion to the wire diameter. For example, at 200 kc it was necessary to use a solder ball 60 mils in diameter on a 6.0-mil diameter phosphor bronze wire. The spacing between the solder ball and the head of the cone may be readily computed from equation (8.1). In practice, it has been found that in most all cases this distance is slightly greater than that given by the formula due to the fact that the free end is restricted to zero slope and for a given crystal and support wire it should be determined experimentally using the values obtained from equation (8.1) as a guide in the design. The diameter of the solder ball that acts as a clamp may also be determined experimentally by

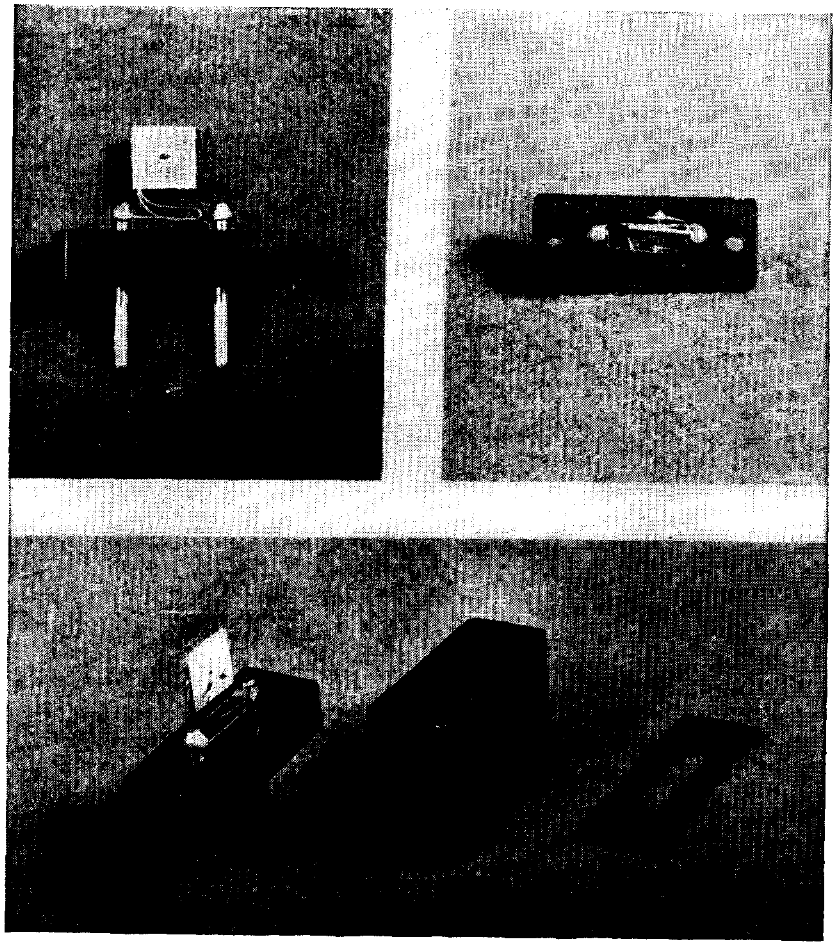

Fig. 8.5—FT-241 crystal mounting.

increasing its size until the standing waves on the wire to the right of the ball are sufficiently reduced. A practical application of this type of support is shown in Fig. 8.5. The top view shows the small wires soldered to the crystal as well as the solder balls that are spaced at points corresponding to the second node on the lead wire from the crystal. These solder balls act as mechanical termination for the lead wires and also as connection to larger size spring wires forming the rest of the shock-proof mounting.

Another type of wire support that has found considerable practical use and is superior to the straight lead and solder cone type of connection is that of the headed wire. This is shown in Fig. 8.6. A headed wire is similar to that of common pin and may be connected to the crystal by sweating the head to the crystal as shown. This has certain advantages over the solder cone in that the head of the wire being a machined part is always constant and the distance *d*, as shown in Fig. 8.6, is the same for all mountings. The amount of solder necessary to sweat thehead tothe crystal is considerably less than in the case of the cone and hence this type of mounting will have less dissipation at the higher temperatures. One other factor not mentioned above is that the coupling between the vibrating system of the wire and the vibrating system of the crystal is considerably reduced by the use of

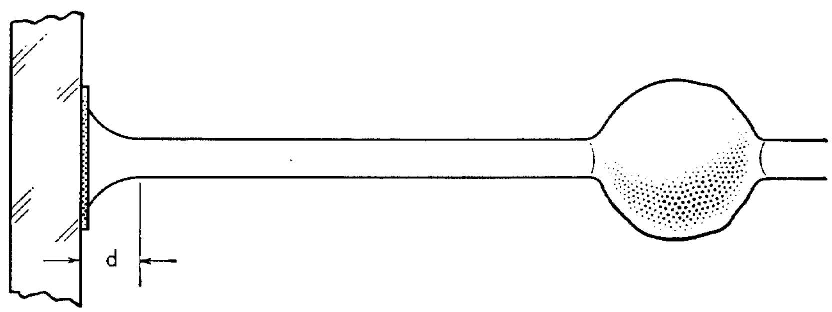

Fig. 8.6—Headed wire type mounting.

the headed wire. This is an important factor in reducing what may be termed a double system of standing waves on the wire. One standing wave system would result from reflections from the clamped end of the wire, while the other would result from reflections between the clamped wires coupled through the crystal. This may be reduced by a reduction of coupling between the crystal and wire vibrating systems.

Measurements have been made on the effect of clamping the wire-supported crystal at various points, on the activity and frequency of several different crystals used in oscillators and filters. Figure 8.7 shows the effect of clamping a 500-kc CT type crystal such as now used in the FT-241 holder. Figure 8.8 shows the same condition for a 370-kc CT crystal. It will be noted that in these two cases with the decrease in frequency of the crystal that the coupling between the wire and crystal has decreased, as shown by a smaller change in frequency and also, that for the lower frequency crystal the change in activity is modified only when the clamp is very close to a loop of motion on the wire. The mountings of these crystals were of the type shown in Fig. 8.4 where the amount of solder in the cone equals that of a solder pellet 20 mils in diameter and 12 mils high.

Figure 8.9 shows the change in frequency as a result of clamping one wire of a four-wire mounting of a GT-cut crystal designed for use as a filter ele-

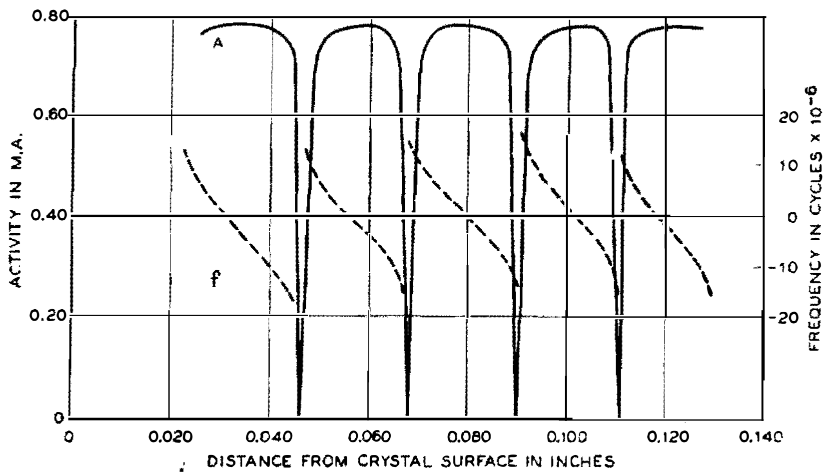

Fig. 8.7—Effect on frequency and activity of clamping one lead of 500 kc. CT-cut crystal.

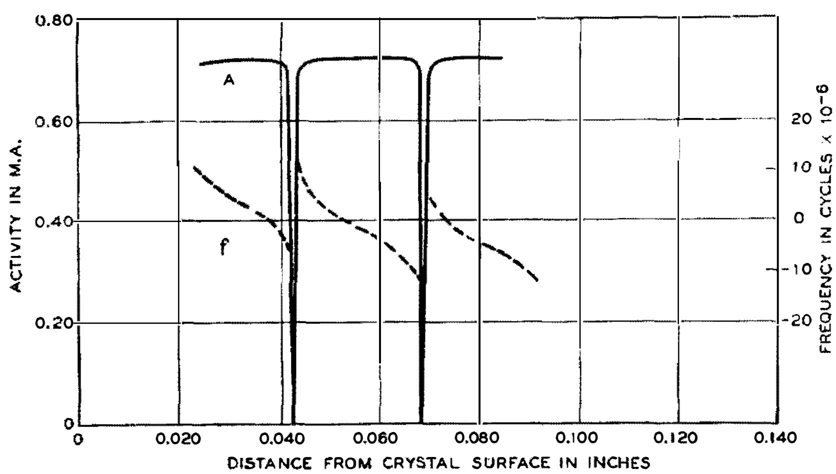

Fig. 8.8—Effect on frequency and activity of clamping one lead of 370 kc. CT-cut crystal.

ment at 164 kilocycles. This change is shown for the lower resonance at 143 kilocycles since this mode would be more affected by clamping. The large deviations in frequency correspond to clamping at the loops of the wire as shown in Figs. 8.8 and 8.9 but the small sudden changes in frequency are a result of a second system of standing waves as previously described. This second system of standing waves results from too much coupling between the crystal and the two oppositely disposed lead wires. It may be reduced by first placing the wires closer to the nodal point and second, using a smaller amount of solder in the cone to attach the lead wire to the crystal. Measurements on this same type of crystal when the above conditions were fulfilled showed practically no effects of secondary standing waves. It is important to keep the energy transmitted to the lead wires low since a soldered connection near a loop of motion resulting from secondary standing waves on the wire will act as a clamp and will materially decrease the resulting Q of the crystal. This is probably the best reason for the use of the headed wire type of lead wherever practical.

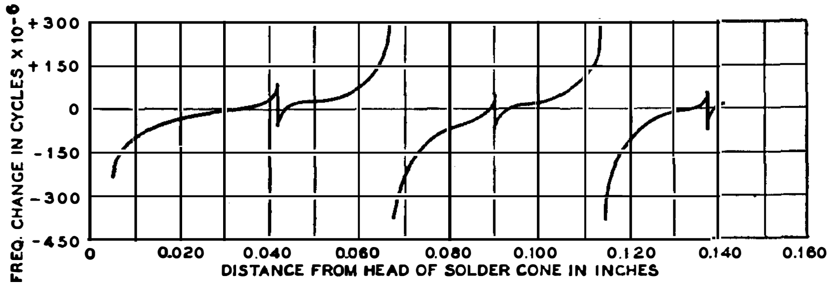

Fig. 8.9—Effect on the frequency of lower resonances of clamping one lead of 164 kc. GT-cut crystal.

8.3 Air-Gap Type Supports

A third form of mounting for quartz crystals is that of the airgap type shown in Fig. 8.10 where the crystal plate is held between two flat electrodes. Two forms of the airgap type of mounting are shown. In Fig. 8.10A the crystal is free to vibrate between two flat electrodes held together to produce a definite airgap of thickness t. In Fig. 8.10B small lands are left on the corners of the electrodes to produce a uniform airgap on each side of the crystal as well as to clamp the crystal plate.

This type of mounting has found its greatest use for oscillator crystals of the AT and BT type. The factor that determines the choice of mount is the ratio of length to thickness of the crystal. For example, when the length is less than 20 times the thickness, clamping the corners of AT and BT type crystals will decrease the activity in proportion to the clamping pressure. This is apparent from a study of the type of motion for these crystals described in Chapter VI. This then indicates that AT and BT type crystals for broadcast frequencies should employ a mounting with the crystal unrestricted as shown in Fig. 8.10A while the higher radio frequency crystals may be clamped as shown in Fig. 8.10B. The clamping pressure will be dependent upon the area of the crystal, its frequency and the amount of activity required. One advantage of the clamped type support lies in the

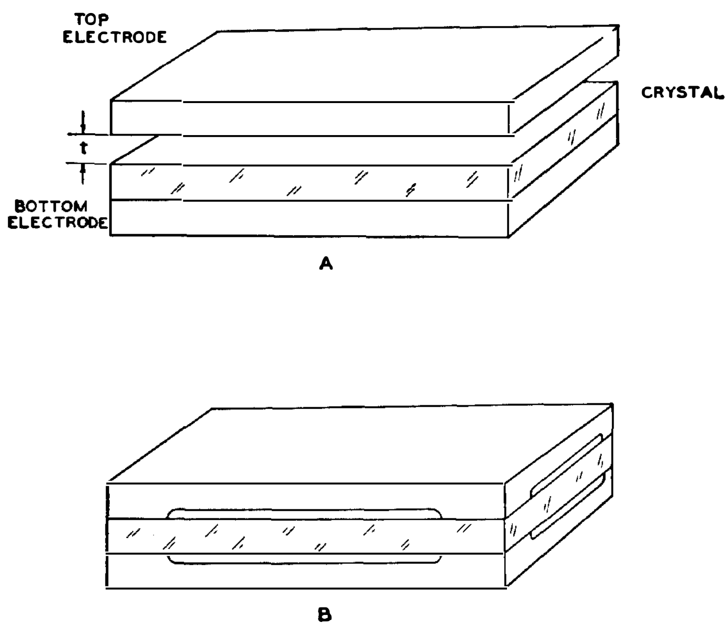

Fig. 8.10—Air gap type mounting.
A—Crystal free.
B—Crystal clamped at corners.

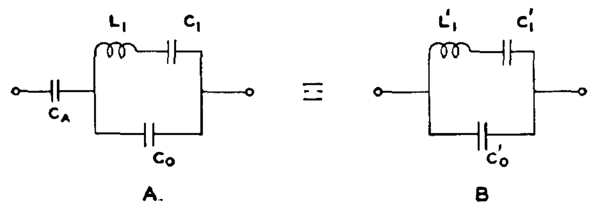

Fig. 8.11—Equivalent circuit of a quartz crystal in an air gap type mounting.

fact that many of the unwanted modes of motion are restricted or dampened to the extent that they will not cause serious dips in the activity characteristic over a wide temperature range. This explains in part the necessity for accurate control of the length and width dimensions for crystals of low radio frequencies using the type of mounting shown in Fig. 8.10A.

The effect of the airgap on the constants of the crystal equivalent circuit may be determined from Fig. 8.11. In Fig. 8.11A is shown the usual crystal equivalent circuit in series with a capacity C_A which represents the capacity of the airgap. This may be reduced to the circuit of Fig. 8.11B where the constants are given by

$$C_0' = \frac{C_A}{C_A + C_0} C_0$$

$$C_1' = \frac{C_A^2}{(C_A + C_0)(C_1 + C_A + C_0)} C_1$$

$$L_1' = \left[\frac{C_A + C_0}{C_A}\right]^2 L_1$$

The circuit of Fig. 8.11B is the same form as that of the original crystal and therefore we may assume that the effect of the airgap is to produce a similar

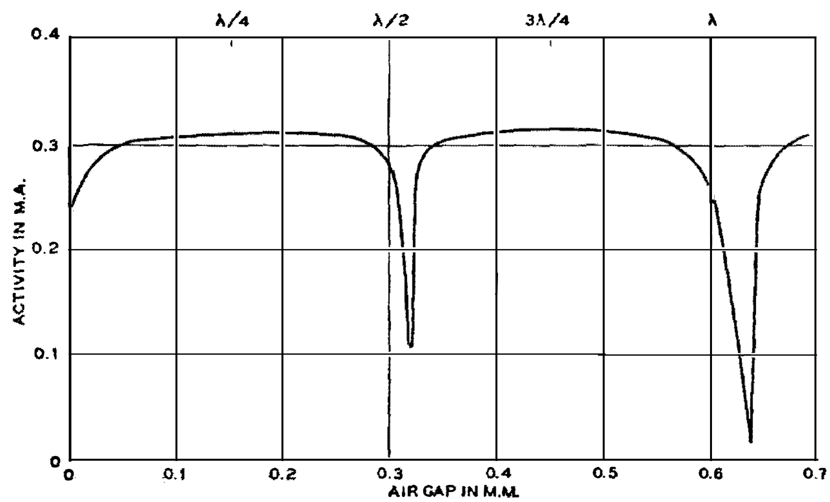

Fig. 8.12—Effect on frequency of the air gap thickness on a 550 kc. AT-cut crystal

crystal of reduced capacity and reduced effective piezoelectric coupling. In the case of oscillator crystals the effect of the airgap is to reduce the activity and decrease the range of frequency adjustment with parallel capacity. For filter applications the effect of the airgap is to produce narrower transmission bands and higher characteristic impedance. One other effect of the airgap results from the propagation of acoustic waves from the crystal.

It is known that most any type of crystal in a vibrating condition will produce acoustic waves in air and if an object capable of reflecting these waves is the proper distance away, these acoustic waves may be reflected back to the crystal surface. The reflections from distances corresponding to even quarter wave-lengths will cause considerable damping while the reflections from distances corresponding to odd quarter wave-lengths will cause very little. The wave-length of a sound wave in air may be readily computed, and since we are interested in multiples of one-quarter wave-length, it is desirable to determine these for a given frequency. This can be computed readily from equation 8.3,

$$\frac{\lambda}{4} = \frac{v}{4f} \qquad 8.3$$

where v is the velocity of sound in air at room temperature and pressure and equals 33,000 centimeters per second. For example, a quarter of a wave-length at 5 megacycles is given by

$$\frac{\lambda}{4} = \frac{33{,}000}{4 \times 5 \times 10^6} = .00165 \text{ cm}$$

which indicates that if t of Fig. 8.10 were made equal to this or odd multiples, there would be very little effect of the electrode on the crystal and if t corresponded to even multiples of a quarter wave-length, we would expect considerable damping. Some measurements of this effect have been made with a low frequency AT-cut quartz crystal and are shown in Fig. 8.12. The sound wave generated by an AT-cut probably results from flexure waves generated by the high-frequency shear wave. It will be noted that when the airgap is equal to even multiples of a quarter wave-length, the activity is considerably reduced. Further, it will be noticed that airgaps in the order of 1/8 of the wave-length may be used and produce very little effect. Since a large airgap reduces the piezoelectric coupling it is desirable to keep this about 1/8 of a wave-length as a maximum unless, in special cases, a reduction in piezoelectric coupling may be tolerated.

APPENDIX D

LOCATION OF MASS ON SUPPORTING WIRE

The impedance to motion transverse to the length of a clamped-free rod at the free end is given by,*

$$Z = \frac{jY_0 Ib^3}{\omega}\left[\frac{\dfrac{Y_0 Ib}{j\omega Z_m}(\ell + \cosh m \cos m) - (\sinh m \cos m + \sin m \cosh m)}{\ell - \cosh m \cos m + \dfrac{Y_0 Ib}{j\omega Z_m}(\sinh m \cos m - \cosh m \sin m)}\right] \qquad (D.1)$$

* From an unpublished memorandum by W. P. Mason.

where Y_0 = Young's modulus
I = moment of inertia of cross section
K = Radius of gyration of cross section

$$b = \sqrt{\frac{\omega_p^2}{Y_0 K^2}}$$

Z_m = moment impedance of free end
$m = bl$
l = length of rod

For the case of a clamped-free rod with no restriction of the free end ($Z_m = 0$) the above equation reduces to

$$Z = \frac{jY_0 I b^3}{\omega}\left(\frac{\ell + \cosh m \cos m}{\sinh m \cos m - \cosh m \sin m}\right) \tag{D.2}$$

The mechanical impedance at the free end would then be zero when m satisfies the equation

$$\ell + \cosh m \cos m = 0 \tag{D.3}$$

For modes above the first an approximate solution of equation (3) is given by

$$m = (n - \tfrac{1}{2})\pi \tag{D.4}$$

For the case of a clamped-free rod with the free end restricted to zero slope ($Z_m = \infty$), equation (1) reduces to

$$Z = -\frac{jY_0 I b^3}{\omega}\left(\frac{\sinh m \cos m + \sin m \cosh m}{\ell - \cos m \cosh m}\right) \tag{D.5}$$

The mechanical impedance of the free end will be zero when m satisfies the relation

$$\sinh m \cos m + \sin m \cosh m = 0 \tag{D.6}$$

For modes above the first an approximate solution to equation (6) is given by

$$m = (n - \tfrac{1}{4})\pi \tag{D.7}$$

In a practical case of a lead wire soldered between a vibrating crystal surface and a ball of solder, m which equals bl cannot be measured accurately since strain will extend some small distance into both masses of solder. It becomes a practical matter therefore to determine m by starting with the assumption that

$$m = (n - k)\pi \tag{D.8}$$

where the extreme values of k would be $\frac{1}{4}$ to $\frac{1}{2}$ and its exact value determined experimentally for a given set of conditions.

In a similar manner by setting the denominators of equations (2) and (5) equal to zero it can be shown that the mechanical impedance of the free end will be infinite when m is defined as

$$m = (n + k)\pi \tag{D.9}$$

where the value of k would be $\frac{1}{4}$ for the free end free and $\frac{1}{2}$ for the free end restricted to zero slope. As before, in a practical case k would assume a value intermediate between $\frac{1}{4}$ and $\frac{1}{2}$.