CHAPTER X

Adjusting to Frequency

By GEORGE M. THURSTON

10.1 AT AND BT CRYSTALS

AT AND BT crystals are thickness vibration crystals, that is, the thickness dimension is the main determinant of the frequency. In the manufacture of these crystals one can picture the shop divided into sections. The first section is concerned with producing quartz blanks, the length, width and thickness dimensions of which are accurately controlled. These dimensions are held to mechanical measurements particularly in respect to the length and width. The thickness dimension may be held either to mechanical measurements or to rough electrical measurements. If electrical measurements are employed the quartz blanks are so dimensioned in thickness that their frequency will be approximately 10 kc below the nominal frequency for which the quartz blanks are intended. The blanks are then turned over to a second section of the shop which is concerned with the final adjustment of the thickness of the quartz blanks to the frequency at which they are intended to be used. The measurements made in this section of the shop are very accurate frequency measurements, mechanical measurements not being accurate enough for final adjustment.

The second section of the shop is concerned also with assembly of the crystals in holders and with making all necessary tests in order to determine if they meet the specifications to which they are being made.

10.2 ACCURACY

The tolerance to which the crystal must be adjusted depends on the purchaser's specification. Actually the tolerance to which the crystal must be ground is appreciably smaller than that called for in the specification, due to the fact that the specification calls for a certain accuracy over a temperature range. The frequency-temperature characteristic of the crystal, which is in many cases a large factor in respect to the specified tolerance, has to be considered and allowed for by restricting the adjusting tolerance.

The thickness of a 5-mc *AT* crystal is a proximately .336 mm. A customary accuracy required for frequency is $\pm 0.01\%$ over a temperature range of 0°C to 60°C which would indicate that the shop tolerance should be roughly $\pm 0.003\%$ at room temperature or a thickness variation of ± 0.00001 mm. To attain this accuracy calls for measurements of precision far beyond that required in optical work.

10.3 Method of Calibration: Calibrating Lap

The crystal is brought to approximately the required thickness in a lapping machine of the general type described in Chapter IX on Sawing, Grinding and Lapping, Fig. 9.24.[1] The final finish lapping is a hand operation, however, since the process is short, and the crystal must be tested for its proper frequency at frequent intervals. This final lapping was formerly accomplished by placing the crystal on a lap like those used in a lapping machine and moving it around with the finger. This method, however, was subject to all the irregularities of the earlier machine methods. To overcome these difficulties, therefore, a new hand lapping outfit was designed and a new technique outlined that gave much improved results, and has greatly expedited the finishing process in the calibrating room.

The objectives of the design were to secure an even pressure over the entire face of the crystal, to allow the crystal to rotate as it passed over the lap, to have the crystal override both inner and outer peripheries of the laps at each passage across it so as to avoid the tendency to excessive grinding on the outer sections of the crystal, and to secure essentially even wear over the entire surface of the lap so that it would remain flat. None of these objectives were very satisfactorily attained with the earlier hand method. It was almost impossible to secure uniform pressure by moving the crystal with the finger, and rotation of the crystal was negligible. In addition, overrunning of the lap was very irregularly if at all obtained, and the tendency to excessive grinding over certain regions of the lap was always present.

To secure evenly distributed pressure on the surface of the crystal, a glass carrier was designed. This is shown at the right in Fig. 10.1. One surface of this carrier is ground optically flat and the other has a small indentation at the center. In operation, a wetted crystal is slid onto the flat surface to which it adheres and is then placed on the lap with the carrier on top of it, and the crystal moved over the surface, by placing the point of the stylus, shown at the left in Fig. 10.1, in the socket in the top of the carrier. Pressure applied at this point is distributed evenly over the surface of the lap in contact with the crystal. Moreover, as the carrier is pushed around by the stylus, the effect of the friction is to rotate the crystal and the carrier, thus giving rotational motion in addition to that of translation.

To secure regulated overshooting of the crystal at both inner and outer peripheries of the lap, a lap holder was designed that would permit the crystal carrier to move off the lap a fixed amount at both its edges. This holder, shown in Fig. 10.1 has a low round projection in the center that fits inside the lap and holds it securely in place. Arising from the center of

[1] Also see "Flatness and Parallelism in Quartz Plates," George Thurston, *Bell Laboratories Record,* June, 1944.

this projection is a cylinder that is smaller than the central opening of the lap by just the amount of overcarry desired. Around the outer periphery of the lap, and the same distance from it as the central cylinder is from the inner periphery, is a ring to limit the extreme outer position of the crystal carrier. The operating technique is to move the crystal in looping arcs between the outer and inner stops, and at the same time to carry it around the lap. Thirty small loops for one round trip of the lap are specified.

As may be observed by reference to the article describing a precision machine lap, this motion is almost exactly the same as that discussed therein. In making the finishing laps, however, hand lapping is much quicker than

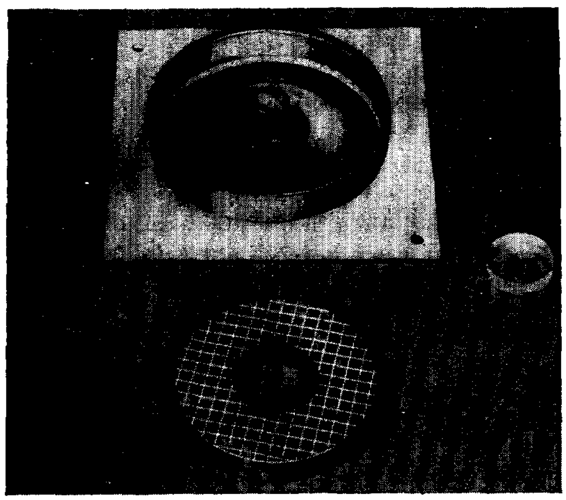

Fig. 10.1—Hand operated lap to grind crystals to a single frequency

the machine lap because the frequent removals of the crystal from the lap to test for frequency, while quite simple with the hand outfit, become complicated and slow with the machine. This new device and technique give the speed of hand lapping and yet retain precision of the best machine lapping. Because of this advantage, the time required to train girls for this hand lapping process has been materially reduced.

Two other methods of adjusting to frequency should be mentioned here: (1), etching to remove material thereby raising the frequency; (2), plating to add material thereby lowering the frequency.

10.4 Surface Finish

The condition of the surfaces of quartz plates is an important factor in quartz oscillators. Improperly surfaced plates will not oscillate with sufficient vigor to be useful. The surface condition is also a determining factor in respect to the frequency stability of the plates.

In the sawing operation where the quartz blanks are cut from the mother quartz, it is possible to shatter the surface of the quartz; it is therefore necessary to cut the blanks somewhat thicker so as to allow for the removal of the shattered surface by lapping.

The lapping operation may also result in surface shattering, particularly if it is done too rapidly or if too high pressures are used.

Experience has indicated that it is very desirable to use a finer grade of abrasive in each succeeding step of lapping, and to completely remove the surface created by the preceding grade of abrasive, ultimately finishing with a very fine abrasive such as $303\frac{1}{2}$ emery. The lapping is done with a mixture of castile soap, water and abrasive. The final surface of the quartz should be free from surface scratches. For most purposes it is not necessary to polish a crystal, since activity specifications can be met by a crystal with unpolished surfaces.

10.5 Contour

The parallelism to which the two major surfaces of the quartz plates are finish-lapped has a great bearing on the electrical performance of the plates. If plates could be made to have their two major surfaces plane parallel to an extremely high degree, excellent performance would be attained. From a practical standpoint is difficult to produce surfaces to such high precision. In attempting to produce such surfaces, a great number of the plates will be lapped with their major surfaces slightly non-parallel thus making the crystals wedge-shaped. The other condition experienced is that the crystals will be somewhat concave in the center portion. Either of these conditions result in crystals which will be unsatisfactory electrically.

In production, then, it is preferable to lap plates not exactly flat and plane parallel but having a definite symmetrical contour with the thickness the greatest at the center falling off uniformly to the edges. The amount of contour should be controlled roughly to $\frac{10^7}{f}$ microns for crystals above 3 mc.

10.6 Effect of Type of Holder

It is highly desirable to make the final adjustment to frequency in the same type of holder in which the crystal is to be used to avoid errors in calibration. In the early types of crystal holders the crystal lay on one flat plate while a second flat plate was set directly on top of the crystal and in contact therewith. The frequency of the crystal was found to change as the top electrode was shifted. This type of holder may be used in the manufacturing process up to the final stage of adjustment to frequency because these variations are small compared to the frequency change to be made in the final adjustment.

In the case of the air-gap type of holder the frequency is affected by the amount and shape of the air-gap. If the air-gap is wedge-shaped, placing the crystal in the holder at various rotated positions will give slightly different frequencies. In the clamped type of holder the electrodes rest on the crystal at its four corners with a very small air-gap. Changing the relative positions of electrodes and crystal by rotating one or the other can change both frequency and activity a little. It is almost impossible to make electrodes identical, so it is usually found that a crystal when adjusted to frequency by one set of electrodes will perform quite differently with another pair. The best practice is to make the final adjustment of a crystal to frequency with the electrodes and holder with which it is to be used, since changing to a different set may cause the frequency to be outside the specified tolerance.

10.7 Aging

Over a period of time crystals have been found to suffer a variation in frequency and activity which may be great enough to spoil them for use under the original specifications. This is known as aging. The methods of finishing the crystals may determine the amount of aging they will undergo.

In the process of lapping, a disturbed layer of quartz is produced on the surface. The lapping process is a pounding and shattering process in which a hard particle of the abrasive gets wedged at spots between the crystal and the lap, and as the lap moves with respect to the plate the enormous pressure per unit area generated under the very small particle of abrasive cracks and shatters a small area of quartz. The cracking and shattering break some particles of quartz completely away from the crystal and they are carried away. Other crackings, however, occur which do not completely detach crystalline material. The crystal surface after lapping thus contains large numbers of minute cracks extending into the crystalline material producing a layer that is not homogeneous and is usually referred to as the "disturbed layer."

When this layer is exposed to moisture, a weathering action takes place. Much of the material contiguous to the cracks detaches itself and falls off. This reduces the loading on the crystal plate, and the frequency rises.

Several methods have been devised for reducing the amount of aging. The aging phenomenon seems to take place to a greater degree when coarse abrasives are used in finishing or when plates are lapped with the abrasive in oil instead of soap and water. Oil gives a faster lapping rate than soap and water with equal fineness of abrasive, just as coarse abrasive gives a faster lapping rate than a fine abrasive in any one liquid. The lapping rate appears to be associated with the number and depth of the cracks produced in the crystal surface. Plates that are lapped with a fine abrasive in a solution of soap and water and then thoroughly cleaned show a relatively small degree of aging.

Aging can be reduced or prevented by several methods. Scrubbing the plate with a brush and soap and water will remove most of the loose material and some of the material that weathers off easily. Etching the surface of the crystals to a degree that removes the disturbed layer to the depth of the lapping cracks, or to where those remaining are too few to cause appreciable aging, is very effective. Both of these methods increase the crystal frequency, and this increase must be taken into account during the adjusting process. The scrubbing or the etching must be final. No lapping to any degree can be done as the final step in frequency adjustment if the full effects of these processes are desired. Another method of preventing aging is to mount the crystal so that no moisture can get at it. In one form this is accomplished by mounting the crystal in a hermetically sealed holder with dry air or a vacuum. Another way, not so thorough, is to cover the crystal surfaces—to the extent possible—with moisture impervious and non-corroding metal films.

10.8 Overshooting

Crystals finished by scrubbing and etching may overshoot their frequency by being accidentally ground too far or etched too long. Although crystals thus treated are useless for that frequency they may be lapped up to the next higher frequency required. If plating facilities are available the crystals may be restored to the frequency passed by loading the surfaces. Silver or gold or some other metal may be plated or evaporated onto the crystals to lower the frequency. However, these processes for restoring to a passed frequency have seldom been found economical because, as a rule, manufacturers receive orders for a number of frequencies over a wide range and it is easier to grind to the next higher frequency.

10.9 Assembly

The final step before testing the crystals is to assemble them in clean holders. The procedure for scrubbing the crystals with soap and water and brush has been mentioned before. The same amount of care should be taken to have clean electrodes. All parts should be free from lint and dust particles which might interfere with the performance of the crystals.

10.10 Dimensioning

Up to this point only the adjustment of the thickness dimension for calibration to frequency has been discussed. However, the length and width dimensions are very important to the performance of a crystal. The necessity for determining the proper length and width dimensions for a crystal of a particular frequency is brought about by the presence of interfering modes of vibration. The theory for the presence of these modes has been explained in Chapter VI. It is shown that the many modes of vibration possible in a single crystal plate provide resonating frequencies ranging from very low frequency to very high. When one of these numerous frequencies is approximately the same as the nominal frequency of the crystal plate determined by the thickness mode of vibration, the coupling between them will cause the crystal to exhibit the usual phenomenon of coupled circuits, that is, the crystal will show resonance properties at either of two frequencies one of which is higher than the highest of the coupled frequencies and the other lower than the lowest. If one were to try and drive a crystal at some frequency in between these two he would find that the coupled extraneous mode had introduced a large amount of resistance into the desired mode lowering the activity of the crystal.

An adequate means for computing the proper size of plates has not been devised to enable one to dimension plates so as to be completely free from couplings. However, it is possible by proper adjustment of the length and width of a crystal plate to find areas in which these complex modes of vibration give the minimum amount of interference. It has been found most expedient from the standpoint of manufacture to construct crystals in a square form. It may be more desirable to depart from square plates where the tolerance on length and width dimension is too small. If one takes a quartz plate and changes the edge dimensions in small increments, always keeping the plate square, and plots the activity (the amount of driving voltage delivered to an oscillator grid) against the square dimension of the plate, a curve will be obtained similar to the one shown in Fig. 10.2. It can readily be seen from this plot that there are only small regions where the activity of the plate is at a peak, and that these regions are quite narrow in respect to the changes in length and width of the plate. By selecting the top activity regions which have the broadest and smoothest characteristic, one can expect to obtain the most favorable dimensions, the tolerance being defined by points where the curve starts to decline. If this curve is replotted, using as the abscissa the ratio of the thickness to square dimension, one can determine the proper dimension for a desired frequency. A check on this method is to take the same crystal edge-ground to accumulate data as in Fig. 10.2, or another crystal with the same dimensional ratio, and grind it down in thickness in small increments through the regions of dimensional ratio covered by the edge-grinding procedure. The activity peaks and troughs will occur at the same points. The curves given in Figs. 10.3 and 10.4 are examples of what may be obtained by determining the dimensions from curves similar to Fig. 10.2 and checking their correctness by making heat run tests on a number of crystals. These test crystals were run over a temperature range of −55°C to +90°C: if the resulting curves were smooth and maintained a fairly constant activity they were considered acceptable. The areas included between the arrowed parallel lines in Figs. 10.3 and 10.4 indicate dimensions for *BT* quartz plates having good electrical characteristics, the center of a region being most desirable. The tolerance allowed by these regions is well within the accuracy obtainable by mechanical

Probable Regions of Good Performance During Temperature Run from −55° to +90°C
Thickness of Crystal = .512 MM Capacity = 32 MMF BT Quartz

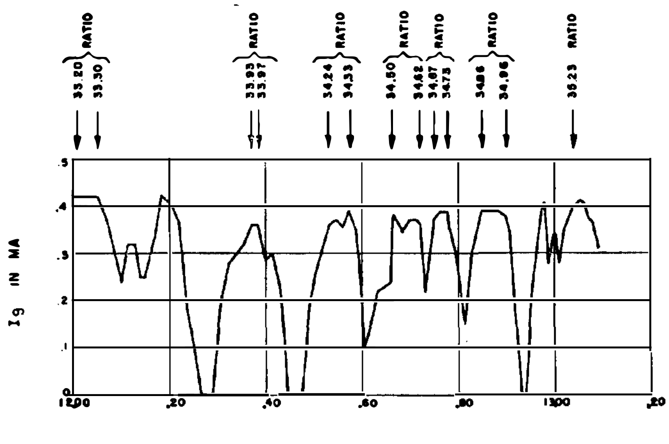

Fig. 10.2—An activity curve for a *BT* crystal as its large linear dimensions are changed, the thickness remaining constant at .512 mm, and the crystal being maintained square. Capacity paralleling the crystal = 32 mmf. Measurements as secured run from right to left. A similar shaped curve is secured by grinding down the thickness only of a square crystal, and plotting the measurements from left to right.

measurements in the shop. These curves are based on the following angular control of cut of the plates:

$$A_1 = 0°\ 0' \pm 15' \qquad A_2 = -49° \pm 15'$$
$$A_3 = 0°\ 0' \pm 15'$$

An indication of the success obtainable through this procedure is given by figures from shop production. Using dimensions for plates between 5 and 8.5 mc from curves similar to Figs. 10.3 and 10.4, 110,000 plates were obtained for calibration over a three months period. Of these 16.5% failed to meet all subsequent tests. This figure includes losses in all subsequent operations, including spoilage by overgrinding in calibration. In a check run on 9000 plates using a different but commercial shop procedure in which dimensions and contours were under more careful control, 8954 were delivered to the customer. Of the .5% that failed, a third of them were unusable because of flaws in the quartz. This unusually low figure for losses is given as an example of how predimensioning and a proper shop procedure can result in low spoilage in the calibration process in suitable quartz blanks.

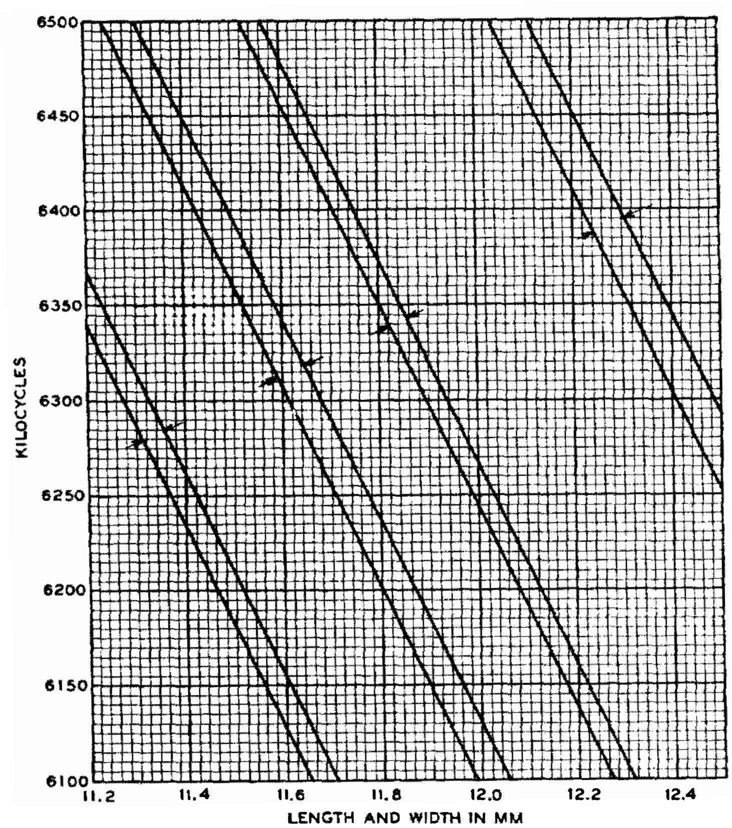

Fig. 10.3—Examples of curves showing probable safe dimensional regions for *BT* crystals. Abscissas are length and width dimensions for a square crystal, and ordinates are frequency using the following formula for determining thickness:

$$\text{Frequency in kc} = \frac{2560}{\text{thickness in mm}}$$

Safe region falls between arrowed parallel lines. A region may not be extrapolated very far outside the limits of the chart as the boundary lines, though sensibly straight within the chart limits, are not straight in theory.

10.11 Calibrating Apparatus

Calibrating apparatus requires a standard frequency or several standard frequencies. A very desirable arrangement where a large number of crystals are to be made which are spaced uniformly apart in frequency is to use a standard precision crystal of great constancy and accuracy, having the frequency of the channel difference. Harmonic generators with tube circuits can supply the necessary harmonics to the calibrating positions. The crystal to be calibrated must be placed between the electrodes of a calibrating

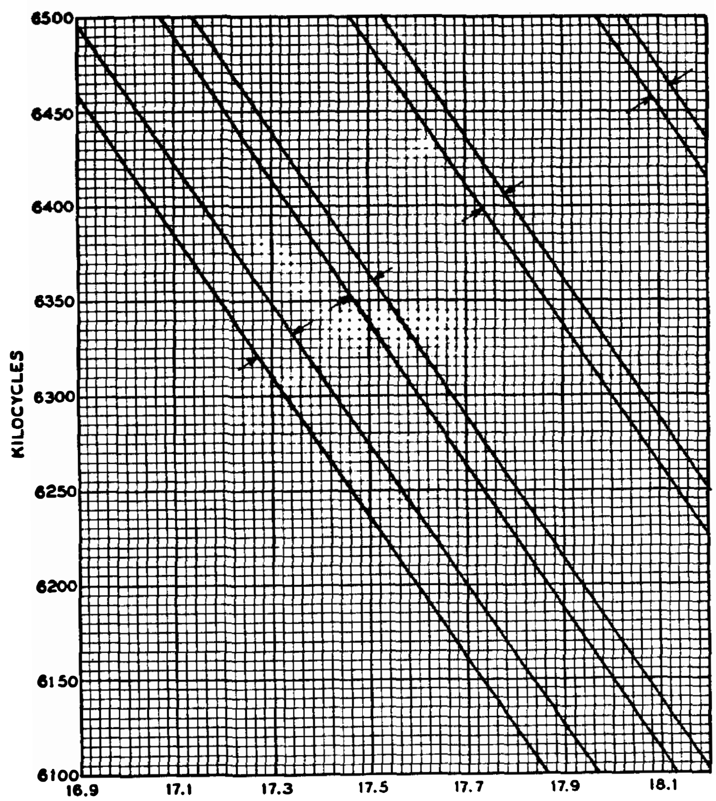

Fig. 10.4—Examples of curves showing probable safe dimensional regions for BT crystals. Abscissas are length and width dimensions for a square crystal, and ordinates are frequency using the following formula for determining thickness:

$$\text{Frequency in kc} = \frac{2560}{\text{thickness in mm}}$$

Safe region falls between arrowed parallel lines. A region may not be extrapolated very far outside the limits of the chart as the boundary lines, though sensibly straight within the chart limits, are not straight in theory.

oscillator and the frequencies compared. This, however, may be beyond the facilities of a small shop. A small shop may use "comparators" or "duplicators" of which there are a number on the market. The comparators, Figs. 10.5 and 10.6 consist of two oscillators and frequency difference indicating equipment. One oscillator will be that in which the crystal to be calibrated is placed. The other will be an oscillator containing a crystal standard which operates at the frequency to which it is desired to adjust the crystal under calibration. This system requires, however, that the standard crystals used in calibrating be close to a desired frequency and be checked occasionally against some more dependable standard. The frequency difference indicator in most of these devices is a cycle counting

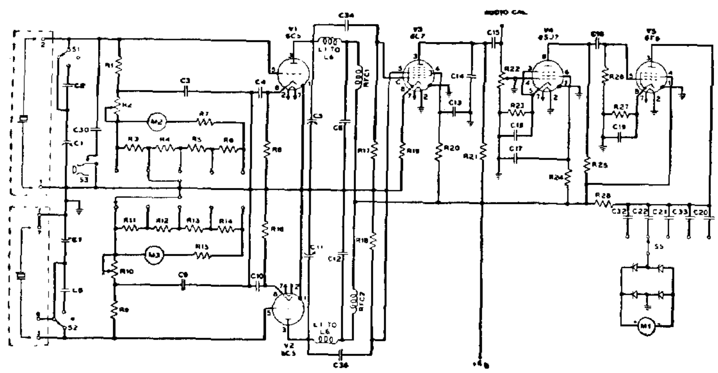

Fig. 10.5—Circuit diagram of a comparator or duplicator

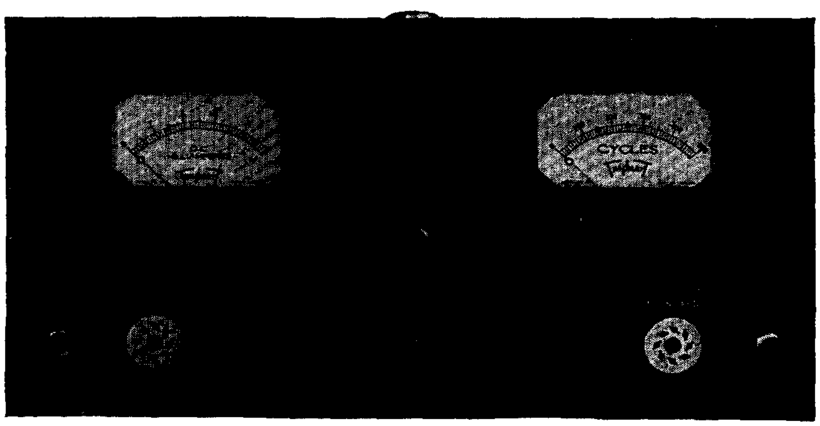

Fig. 10.6—Comparator or duplicator embodying the circuit shown in Fig. 10.5

circuit in which a direct current is produced proportional to the number of cycles rectified. By this means the cyclic difference may be marked on the dial of a meter.

The original method of comparison is to use a variable oscillator which is adjusted so as to operate at the frequency of the oscillator holding the crystal being calibrated. The adjustment to that frequency is determined either by beat notes with telephones, beats on an ammeter, or Lissajous figures on a cathode-ray tube. It then becomes necessary to determine the frequency of the electrical oscillator in turn. This can be done by precalibration using standards to determine known calibrated points.

10.12 Heat Runs

Crystals which must be guaranteed over a wide temperature range must be tested over that range. These ranges go as low as $-55°C$ and as high as $+90°C$. To reach the cold end of the range refrigerators may be used and the coolant which appears to be most economical is solidified carbon dioxide, usually known as dry ice. The test runs are most easily made by starting at the low temperature controlled in a dry ice refrigerator by thermostatically regulating a heater. There are two methods by which test runs are made. One is to place the crystal in a test oscillator individually and vary its temperature over the entire range watching the activity and frequency indicators. A blower and heat coil are used to raise the crystal temperature at the hot end of the run. A thermostatically controlled and adjusted oven must be used to insure that the crystal is fully heated to the highest temperature; or the process must be controlled and timed, using a special crystal holder with an inserted thermocouple to calibrate the process and insure that the temperature limits are reached.

A second method is to place a large number of crystals in a container whose temperature is varied over the entire range. The crystals are tested successively and intermittently. This method can be made almost automatic by design of suitable equipment.

10.13 Test Set

It has been customary for many years for crystal manufacturers to measure the frequency and activity of crystals in the circuits with which they were actually to be used. Seldom if ever did a set designer express the performance desired of a crystal in terms of impedance, voltage across or current through the crystal, frequency, and rectified grid current. The designer took the easier path of saying the crystal should give some certain performance in the set being designed, and supplying a sample of the set's oscillator in which to test the crystals. This meant that crystal manufacturers accumulated and were required to keep a large stock of oscillator apparatus for use in calibrating crystals.

To improve this situation, a method and a test set have been developed which permit the circuit with which a crystal is to be used to be accurately simulated in its essential respects so that frequency and activity may be measured under conditions equivalent to normal operation. Activity is measured by a circuit incorporated in the test set, but the frequency is to be measured by external associated equipment, of any suitable type. The set is known as the D-151288 Crystal Oscillator Test Set.

The characteristic of a circuit with which a crystal is to be used that chiefly affects the activity and frequency is the capacitance it places in shunt with the crystal. One of the major features of the new test set, therefore, is an arrangement to permit the equivalent capacitance to be connected across the crystal. This is not as easy as it sounds—particularly for crystals of very high frequency. Every element of a circuit—even switches, contacts, and leads—has capacitance associated with it, and only extreme care in preparing the design can provide a circuit that permits precise control of the shunt capacitances. Every element of the circuit must be carefully specified, and no element or part can be used that will have different characteristics under varying conditions. Since the test set is used as a shop standard reference circuit, all units constructed must have similar characteristics within close limits, hence once the circuit has been designed and every element specified, no substitution can be allowed, since a change in characteristics would be bound to follow.

The activity of a crystal is a qualitative expression of the amplitude of the voltage appearing across the faces of the crystal as it oscillates. It is measured by the amount of current in the grid circuit of the vacuum tube with which the crystal is directly associated. In the last analysis, of course, it affects the output of the tube, but the output is also affected by the tuning of the plate circuit. A circuit for measuring crystal activity must thus provide for placing a precisely known capacitance across the crystal, for measuring the grid current in the associated oscillator tube, and for tuning the plate circuit to the desired frequency. In addition, a connection to the output must be provided so that the frequency can be measured. The circuit by which this is accomplished in the new test set is shown in Fig. 10.7.

Shunting capacitance for the crystal is provided by a fixed condenser *C*2 and an adjustable condenser *C*1. A three-position switch, *D*1, permits connection to *C*1 alone, to *C*1 and *C*2 in series, or to neither, in which case the shunting capacitance is merely that of the remaining elements of the input circuit.

Grid current is read on a milliammeter with an adjustable resistance in series with it, and with an adjustable shunting resistance that may be inserted by operating switch *D*4. Both of these resistances are adjusted when the set is calibrated. The value of the shunting resistance is made to equal the resistances of the meter itself so that when the switch *D*4 is closed, the meter will read just half the current it read before. The operation of *D*4 thus has the effect of doubling the range of the meter.

For tuning the plate circuit of the vacuum tube, two controls are provided. One is a six-point switch that selects one of six tuning coils, each used for one frequency band in the range from .43 to 31 mc. The other controls the adjustable condenser *C*5.

A regulated plate power supply unit, shown in the lower part of Fig. 10.7 is included in the test set. It consists of a full wave rectifier employing the tube *V*2, and two regulator tubes *V*3 and *V*4. Before the set is put in operation, *R*3 is adjusted to give a specified current through *V*3 and *V*4. At this current, the potential across *J*3 and *J*4 is regulated to limits of ±2%. Tubes *V*3 and *V*4 will then hold the voltage within these limits by drawing more or less current through *R*3 as the voltage of the rectifier varies.

Before using the test set for the first time, and periodically thereafter, it should be checked to make sure the resistance in series with the milliam-

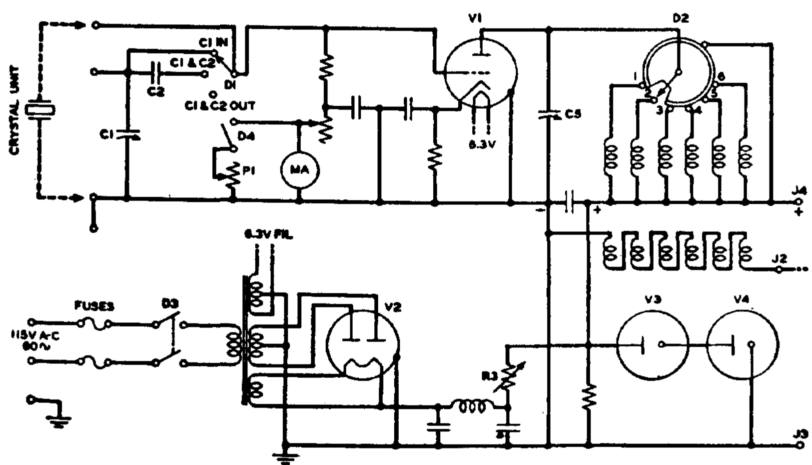

Fig. 10.7—Circuit diagram of the D-151288 Crystal Oscillator Test Set

meter is of the correct value, and that the characteristics of the tube *V*1 are those required for proper operation. For this purpose an alignment coil, provided with the set, is plugged into the crystal socket, and a reading made on the milliammeter. Only tubes giving a grid current within a specified range are usable.

The meter and all the controls are mounted on the front panel of the test set as shown in Fig. 10.8. At the lower left is the main power switch, *D*3, with the fuses immediately above it. To the right of these is switch *D*1, and to the right of that is the receptacle in which the crystal unit to be tested is plugged. Above these is the dial controlling *C*1. Immediately below the meter is the switch *D*4, and just to the right and below the meter are jack terminals *J*3 and *J*4 with a connection for terminal *J*2 between them. This terminal is used for connecting to the frequency-measuring equipment. To the right of the meter is the dial for controlling C5, and at the lower right of the panel is the switch D2 that selects the desired tuning coil.

To make a test, the crystal is plugged into the set, and switch D1 and the dial for C1 are adjusted to give the shunting capacitance with which the crystal is designed to operate. The capacitance value for various positions of D1 and settings of C1 are shown on a chart accompanying the test set. Switch D2 is then operated to select the proper tuning coil for the crystal frequency, and then C5 is turned to give a maximum reading on the meter. Should the reading be off scale, D4 is pressed to halve the current through the meter. With this button pressed, the actual grid current is twice the reading of the meter. The reading of activity thus obtained may then be compared with the required value.

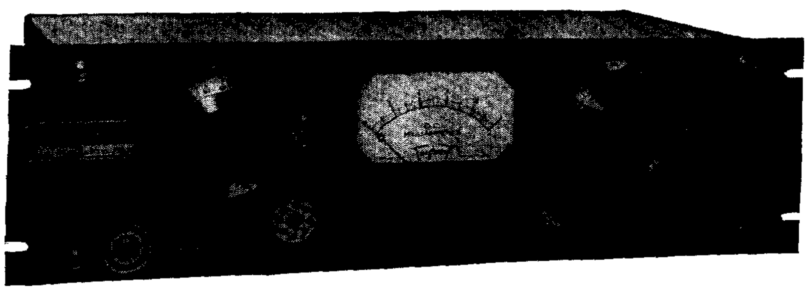

Fig. 10.8—The crystal oscillator test set

To measure the frequency of the crystal, the dial for C5 is turned to the left to reduce the reading of the grid meter to half its maximum value. A reading is then made on a frequency-measuring set used in connection from J2. The six small coils shown in this lead in Fig. 10.7 are each coupled to one of the tuning coils, and supply sufficient voltage for measuring the frequency.

It is to be noted that activity and frequency measurement are made with different adjustments of the plate tuning. The reasons for it are as follows. The activity measurement is made with the plate tuning adjustment that will give a maximum reading. The operating frequency is then slightly different from its operating frequency in the set in which it is to be used, but the relative activities of crystals at the two frequencies are so closely alike that any error introduced is very small compared to errors that would be introduced by trying to adjust the plate circuit to give the actual operating frequency of the crystal in its ultimate set. A maximum is easy to observe and the test rule is simple. As regards adjustment for measuring frequency, a crystal oscillator nowadays is seldom adjusted to give maximum power. The change in constants of the elements in an oscillator, other than the crystal, over a temperature range such as $-55°$ to $+90°C$ is often such as to throw the adjustment out from the maximum power point so that the output will vary with temperature. If the change in frequency is in the wrong direction, the oscillator will stop. The preferred and now practiced method, therefore, is to design the oscillators with an adjustment that is not maximum power adjustment, but one providing about one half the maximum current so that any change in circuit constants by temperature will not cause the oscillator to cease operating. The chosen point is one where reaction of the plate circuit tuning upon the frequency is small or a minimum.

This set has proved to be a most satisfactory reference oscillator. A form of it has been adopted by the Signal Corps as one of its standard test sets. It is specified for use on Army and Navy contracts for certain types of crystals and is employed in a number of plants making crystals for apparatus designed for use by the armed services.