METHOD AND APPARATUS USED IN TESTING PIEZO OSCILLATORS FOR BROADCASTING STATIONS

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ABSTRACT

Piezo oscillators are the most suitable frequency standards thus far devised for use in radio broadcasting stations. A piezo oscillator may be used either to check the frequency of the station or to control its frequency. Most of the piezo oscillators tested by the bureau are for use in checking the frequency of the station. Piezo oscillators are capable of high precision in the measurement of their frequency if a beat note is produced by adjusting another generator to a similar frequency. This principle is employed in the methods and apparatus described in the paper.

After preliminary tests to determine the suitability of the quartz plate and its fundamental frequency, the piezo oscillator is kept in a temperature-controlled room for not less than two days, during which frequency measurements are made.

The method consists in measuring the frequency of the piezo oscillator under test in terms of a 200 kc temperature-controlled piezo oscillator. This is accomplished by adjusting a radio-frequency generator to the frequency which the piezo oscillator under test should have. This adjustment is made by using harmonics from a 10 kc generator which is kept accurately set in terms of the 200 kc standard by observing a special form of beat indicator. The frequency difference between the test piezo oscillator and the generator set in terms of the standard is measured by comparison with an audio-frequency generator. A frequency meter of special design is used to check the frequency difference and determine the sign of the correction to be applied. The method described is also useful in the calibration of frequency meters and the measurement of station frequencies.

CONTENTS

I. PIEZO OSCILLATORS AS FREQUENCY STANDARDS FOR BROADCASTING STATIONS

A broadcasting station, to maintain its assigned frequency, must be provided with an accurate frequency standard. A piezo oscillator is the most suitable frequency standard thus far devised. It is a generator of radio-frequency current, the frequency of which is determined primarily by the dimensions of the quartz plate used. The bureau's service to the broadcasting stations consists of measuring the frequency of the piezo oscillator, or adjusting the quartz plate so that the piezo oscillator has the frequency to which the station is assigned, and issuing a test certificate. This service is one of the classes of radio tests undertaken by the bureau.

A piezo oscillator may be used in either of two ways in maintaining a station on its assigned frequency; first, it may be used for checking the frequency of the station; second, it may be used to control the frequency of the station. Tests at the bureau are usually limited to piezo oscillators intended for use in the first way mentioned because of the practical difficulties in submitting a complete piezo oscillator intended to control the frequency of the station. If the broadcasting station uses a piezo oscillator which is maintained at a constant temperature, the complete temperature-control equipment should be submitted with the piezo oscillator so that the test can be conducted at the desired temperature and under the conditions of use.

The bureau will undertake to adjust a piezo oscillator to the frequency of a station if the frequency as received is not more than 1 per cent below that desired, but will not accept it for adjustment if the frequency is above that desired. Experience in adjusting quartz plates by grinding demonstrates that no guarantee can be made of obtaining satisfactory results. This frequency adjustment is the final step in a series of operations which are required in a technical manufacturing process. Data taken by the Bureau of Standards and other laboratories on the behavior of quartz plates as their dimensions are changed, show that there is a small probability of obtaining a suitable frequency standard by submitting a single quartz plate for adjustment, and this type of test is not encouraged. A more satisfactory type of test, both from the standpoint of the bureau and the station, is to measure the frequency of a piezo oscillator which has been completed and adjusted to frequency by the manufacturers and which operates initially in a satisfactory manner.

II. TESTING METHOD

While the apparatus and method of use reported herein were developed with the idea of applying them to the testing of piezo oscillators having frequencies within the broadcasting band, it was found that the system could be applied with considerable advantage to other tests, such as the measurement of the frequencies of broadcasting stations and the calibration of frequency meters.

A test method and the standards used in calibration work should be capable of a precision at least ten times that of the apparatus to be tested. The precision with which a given adjustment of the apparatus under test can be reproduced should be a guide as to the precision and accuracy of the system to be employed in the test. As the system of measurement to be described is capable of a precision of setting of better than 1 part in 1,000,000, it would be a waste of effort, for example, to use the system to its limit in testing a commercial frequency meter which is only capable of setting to 1 part in 5,000. Piezo oscillators are capable of high precision of measurement, but the fact that an extremely precise measurement of the frequency of the piezo oscillator can be made gives no indication whether the device will be a satisfactory frequency standard for a broadcasting station. Such precise measurement, however, enables one to determine how much the frequency of the piezo oscillator is changed by varying the conditions of operation, and hence to estimate its ability to maintain its frequency after shipment.

As the high precision possible in measurements of the frequency of piezo oscillators depends upon measurement of frequency differences, a brief discussion of how the frequency differences are produced may assist in a better understanding of the paper by those not familiar with such measurements. In any type of radio-frequency generator the greatest amount of power available is present at the fundamental frequency, which depends upon the value of the inductance and capacity of the resonant circuit. Power is also present at other frequencies which are integral multiples of the fundamental frequency. Although the power available at the harmonic frequencies is very small and decreases as the harmonic number increases, yet it is suffi-

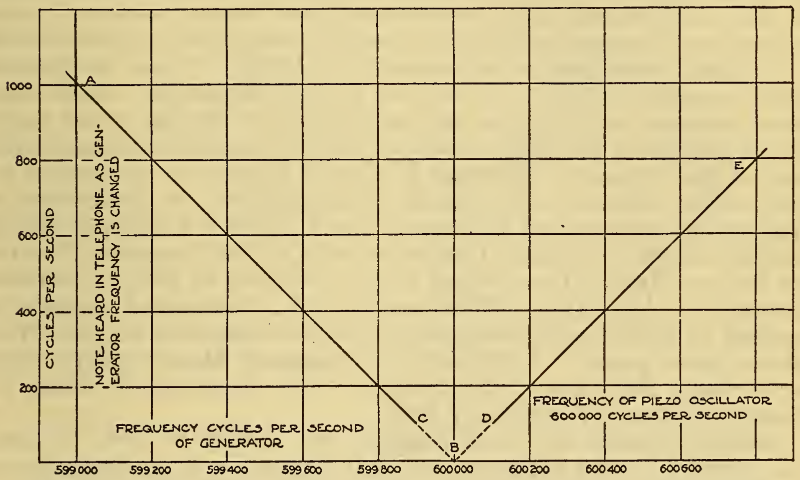

FIGURE 1.—*Beat note produced between piezo oscillator and a radio-frequency generator whose frequency may be changed*

cient to operate a sensitive device, such as a telephone receiver. By means of suitable amplification, harmonics as high as the two-hundredth and higher may be employed in measurements.

If a piezo oscillator having a fundamental frequency of 600 kc is assumed to be in operation, loosely coupled to a radio-frequency generator operating at 599 kc, telephone receivers suitably connected to the piezo oscillator or generator will give an audible response or musical note of 1 kc (1,000 cycles), as shown at *A* in Figure 1. The 1,000-cycle note is the difference in frequency between the radio-frequency generator operating at 599,000 cycles per second and the piezo oscillator operating at 600,000 cycles per second. If the frequency of the generator is gradually increased, as represented by line *AB* (fig. 1), the difference in frequency between it and the piezo oscillator becomes less, and, consequently, the audible note heard in the telephone receivers becomes lower. As the frequency of the generator is slowly increased by turning a condenser dial, a setting of the condenser will be reached corresponding to point *C* (fig. 1), where the telephone receiver is silent, because the frequency is below audibility. If this dial setting is noted and the dial turned slowly in the same direction as before, it may be found that the telephones do not give a response over a certain number of divisions change on the dial until a frequency represented by point *D* (fig. 1) is reached. This condition of silence in the telephones is often referred to as "zero beat," because the impulses or beats in the telephones can not be heard for they are below audibility. While the lower limit of audibility is usually taken as 16 cycles per second, the average telephone receiver will not respond to so low a frequency. For the purpose of clearness in Figure 1, and to emphasize the fact that a zero-beat adjustment is not precise, the lines *AB* and *BE* are shown dotted near their lower ends, indicating no response in the telephones, although the region of zero beat is usually more definite than indicated. A further increase in the frequency of the generator from point *D* toward *E* (fig. 1) increases the frequency difference or beat frequency between generator and the piezo oscillator. Although frequencies in the neighborhood of the fundamental have been considered, similar results may be obtained using harmonics from either or both sources.

A much more precise adjustment at *B* (fig. 1) can be obtained using apparatus which will respond to low frequencies. Such apparatus includes oscillographs and beat-indicator circuits, which couple to the generator and piezo oscillator and will produce a visual indication of the frequency difference of a small fraction of a cycle per second. The operation of a visual beat indicator as applied to low frequencies is described on page 214 of a paper "A Method of Calibrating a Low-Frequency Generator with a One-Frequency Source," by Sylvan Harris, Proceedings of the Institute of Radio Engineers, Volume 14, April 1926. The operation of a visual-beat indicator as applied to radio frequencies is similar and is described on page 275 of the author's paper, "A System for Frequency Measurements Based on a Single Frequency," Proceedings of the Institute of Radio Engineers, Volume 17, February 1929.

Another manner in which point *B* (fig. 1) may be used although the generator is not adjusted to that frequency, is to set the generator to such a frequency that the frequency difference between it and the piezo oscillator operating at point *B* is equal to the known frequency of a tuning fork. Harmonics of the tuning fork may be used, depending upon the ability of the operator to distinguish differences in the pitch of two notes. An operator having a "musical ear" can readily use this method, although results obtained by an operator not so gifted might be unreliable.

A very precise adjustment of the generator at the frequency corresponding to point *B* (fig. 1) can also be obtained by employing another radio-frequency generator, which is operated at some frequency having a harmonic within, for example, 500 to 1,500 cycles per second of the frequency at *B*. This method has been described on page 28 of an article "Frequency Standardization," by J. K. Clapp, Journal of the Optical Society of America and Review of Scientific Instruments, Volume 15, 1927.

The circuits employed in the testing of piezo oscillators make use of the principles outlined in the above paragraphs.

As the piezo oscillators to be tested are capable of precise measurement, it becomes necessary to use a standard for the testing work whose frequency is accurately known and maintained constant. The choice for the standard was a piezo oscillator which operates under constant conditions as to temperature and voltages applied. Its frequency is checked at least once a week by intercomparison with other temperature-controlled piezo oscillators. The frequencies of all piezo oscillators for broadcasting stations are referred to this one standard by means of the apparatus described below.

As the piezo oscillators to be tested for broadcasting stations have frequencies which are multiples of 10, beginning at 550 kc and ending with 1,500 kc, a system giving frequencies spaced 10 kc apart is convenient for test purposes. A 10 kc generator was accordingly made a part of the apparatus and is precisely adjusted to 10 kc. It is, in fact, manually controlled and slightly readjusted when necessary, rather than automatically held at 10 kc. The reason for this arrangement is that it may be desirable to set the 10 kc generator to some other frequency, such as 15, 25, 50, or 100 kc, when used in other

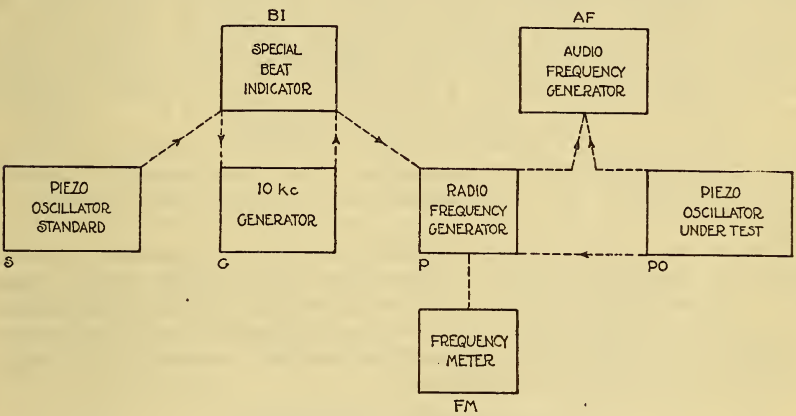

FIGURE 2.—*Apparatus used in testing piezo oscillators for broadcasting stations*

The dotted arrows indicate how the various pieces of apparatus work with the remainder of the equipment.

measurement work, in which case the harmonics would be spaced farther apart and would be of a lower order and, consequently, stronger. This permits a great extension of the frequency range of the system. The same piezo oscillator can be used and the generator will give harmonics spaced at almost any desired intervals, thus providing a very flexible system.

It should also be pointed out that a piezo oscillator of almost any value can be selected and used as the standard in a manner similar to that here described. The harmonics obtained may not be convenient decimal values, but calculations can always be made and the usefulness of any piezo oscillator greatly extended.

The system herein described is best explained by reference to Figure 2, which shows schematically the apparatus as used. The system includes: A temperature-controlled piezo oscillator, *S*, the frequency of which is accurately known, in terms of which the measurements are made; a 10 kc vacuum tube generator *G*, capable of very precise frequency control, and giving a very constant frequency; a radio-frequency vacuum tube generator *P*, covering the range of frequencies desired; the piezo oscillator to be calibrated, *PO*; a calibrated frequency meter *FM*, for determination of the order of the harmonics of the generator *P* in terms of generator *G;* a calibrated audio-frequency generator *AF*, capable of precise adjustment; a special form of combined beat indicator and generating detector *BI*, by means of which the operator maintains the various elements of the system in the frequency relationship desired. The method of operating the apparatus is given below.

III. DESCRIPTION OF APPARATUS

1. TEMPERATURE-CONTROLLED ROOM

Very few of the piezo oscillators submitted for test have been equipped with temperature-control apparatus for maintaining the quartz plate at a constant temperature. Prior to the installation of the temperature-control equipment in the testing laboratory, a variation of 20° C. in 24 hours was possible during the winter months and half this variation during the summer months. Considering a mounted quartz plate having a frequency of 1,000 kc and a temperature coefficient of the order of 0.003 per cent per ° C., a change in temperature of 10° C. would produce a change in frequency of 0.3 kc, which could be indicated on an ordinary frequency meter. The need for a room where the temperature can be maintained constant is evident.

The room available for installation of the temperature-control apparatus was about 21 feet square by 10½ feet high on the main floor of the Radio Building. The installation of a 2-horsepower cooling system for summer and a 5-kilowatt electric heater for winter, controlled by suitable thermostats, has enabled the room to be maintained at the required temperature.

2. FREQUENCY STANDARD

The standard in terms of which the frequencies of piezo oscillators are measured is a 200 kc temperature-controlled piezo oscillator. This type of piezo oscillator has been described by Worrall and Owens in an article entitled "The Navy's Primary Frequency Standard," in the Proceedings of the Institute of Radio Engineers, pages 778–793, volume 16, June, 1928. Some changes in the method of operation and use have been made. The piezo oscillator is inclosed in a specially constructed cabinet which is maintained by means of a mercury thermostat at such a temperature as to give a frequency of 200,000 cycles. This cabinet is located in the constant-temperature room. Heat is provided by means of electric lamps placed in the outer sides of the box, and the air is circulated by means of a fan. The thermostat is placed in the air stream in a position to give the most sensitive temperature control. Under usual conditions no change in the reading of a thermometer graduated in 0.1° C. can be observed.

3. GENERATORS

There are three different generators or oscillators required in the testing work: (1) A small generator which may be adjusted to 10 kc; (2) a generator covering the radio frequencies at which tests are to be made, hereafter called the "power generator"; and (3) a generator of audio frequencies.

The 10 kc generator employs a 5-watt vacuum tube in a Hartley circuit in which a 2-plate variable air condenser permits very minute adjustments in frequency.

The power generator uses the tuned-plate circuit and a 250-watt tube with 600 volts on the plate. Slow-motion devices on the variable condensers permit the precise adjustment of the generator to the desired frequency. It is equipped with a condenser-switching mechanism which assists in rapidly obtaining zero beat with a piezo oscillator. This mechanism changes the frequency from a point above zero beat to a point below zero beat by operating a switch handle. When the note heard on either side of zero beat is the same, the midposition of the switch gives zero beat. This is accomplished by changing the variable condenser slightly.

The audio-frequency generator is a commercial product. The low frequencies are produced in a tuned-plate generating circuit using a 5-watt tube, and the output is amplified by another 5-watt tube. A filter circuit is provided so that the harmonics above various specified frequencies, as indicated by a switch, are reduced to a minimum.

4. SPECIAL BEAT INDICATOR

The special beat-indicator circuits used are the result of an attempt to make possible the precise adjustment of the frequency of one circuit to that of another and not have an interaction between them which may change the frequency of the standard. The beat-indicator circuits used not only accomplished the desired results, but were found to have other important uses in the measurement system.

Essentially, the beat-indicator circuit shown in Figure 3 is a generating-detector circuit. A 1,000-turn coil in the grid circuit couples to the 10 kc generator *G* and to the output of the piezo oscillator *S*. A 600-turn coil in the plate circuit couples to a coil of 8 or 10 turns in series with a crystal detector and direct current microammeter *A*, which gives the visible indication. An audio-frequency transformer is connected in the plate circuit as shown, and telephone receivers or a 2-stage amplifier may be connected to the secondary winding of the transformer as desired. A detector tube is at times connected in ahead of the 2-stage amplifier and serves to increase the sensitivity of the system. A small pick-up coil is sometimes connected to the input terminals of the detector tube, and serves to increase the coupling between the power generator and the 10 kc generator.

5. FREQUENCY METER OF HIGH RESOLVING POWER

In the course of the development and improvement of frequency standards and apparatus a few years ago, the need was felt for a frequency meter capable of more precise measurement and greater accuracy. About 1925 the frequency meter to be described was constructed, although an improvement in the method of resonance indication has recently been added. The frequency meter as originally constructed was found to be more than capable of the precision expected. It soon was found to be indispensable in frequency measurements made during the adjustment of quartz plates to a desired frequency, as requests for such work began to be received.

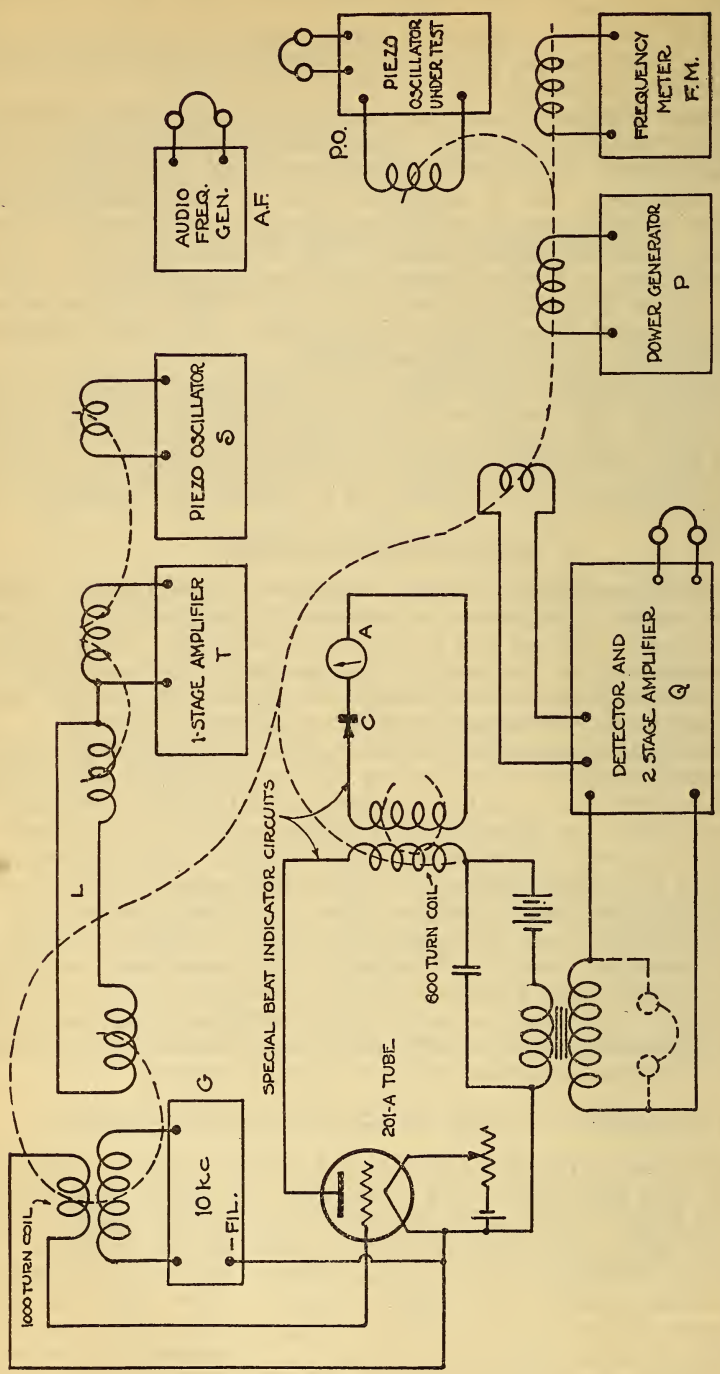

FIGURE 3.—*Schematic diagram of apparatus used in testing piezo oscillators, showing electromagnetic coupling between different units by dotted lines*

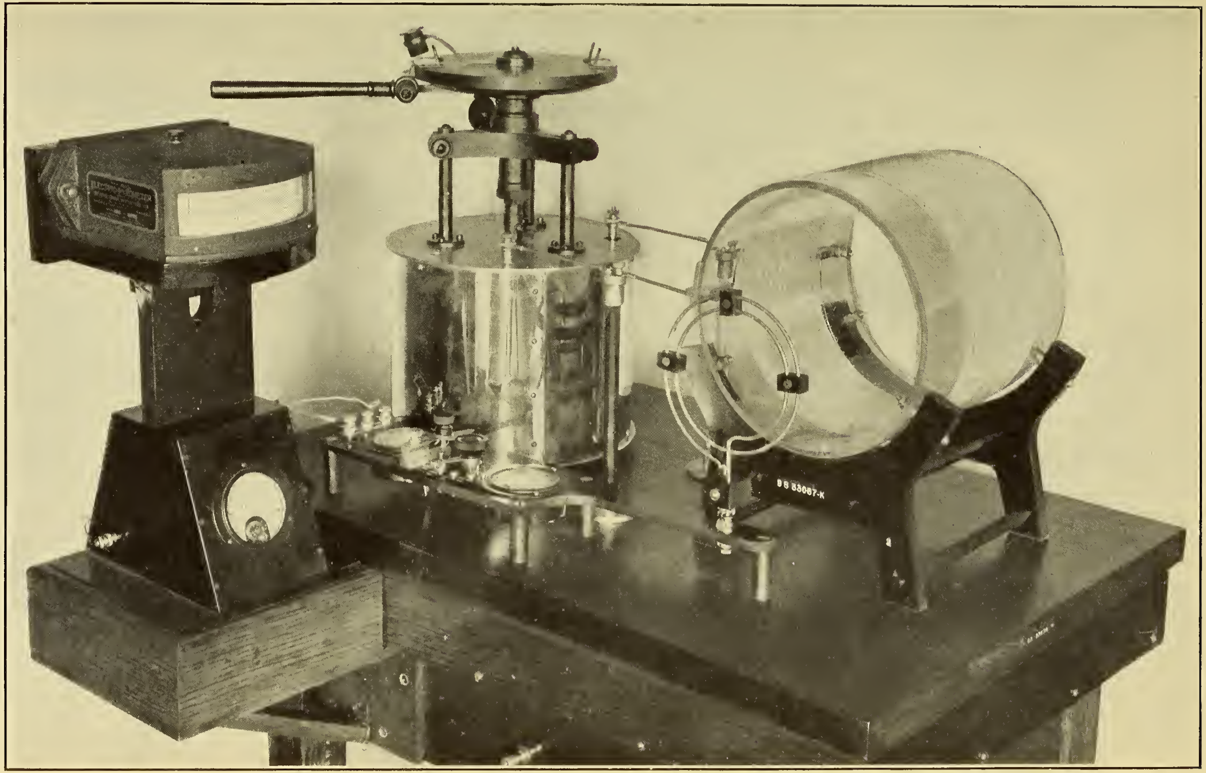

FIGURE 4.—*Special frequency meter used in measuring frequency differences*

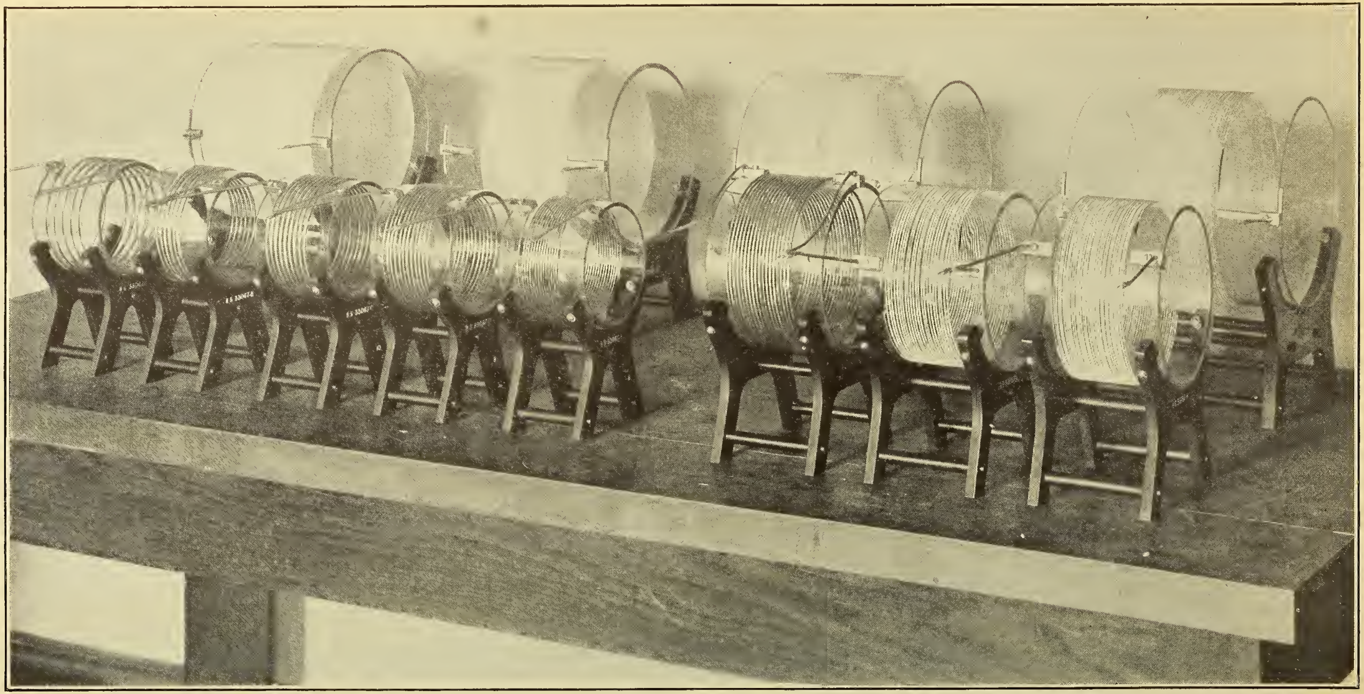

FIGURE 5.—*Series of inductors used on frequency meter shown in Figure 4*

Frequency range covered, 170 to 5,350 kc.

It is still in use for adjustment work or where small changes in frequency are to be measured.

The frequency meter is shown in Figure 4, and the series of coils for it is shown in Figure 5. The condenser is made up of two air condensers, one fixed and the other variable, mounted within the cylindrical shield. The condenser is provided with a special scale and vernier taken from a transit obtained from the United States Coast and Geodetic Survey. The scale is graduated throughout the circumference in sixths of degrees. With a vernier of 60 divisions it is possible to read a movement of 10 seconds of arc, or approximately 0.003°. This is much higher precision in scale reading than is necessary to obtain a fairly high degree of precision in frequency measurement. In practice it is convenient to use but 10 main divisions on the vernier, which means reading the condenser scale to approximately 0.016°. When such agreement in the condenser reading is obtained, the precision of the frequency measurement is 0.003 per cent.

The maximum capacity of the condenser is approximately 400 $\mu\mu$f, half of which is in the fixed portion. This gives a capacity variation of 200 $\mu\mu$f and a minimum capacity of 200 $\mu\mu$f. The movable plates of the condenser are so shaped as to give practically a straight-line percentage frequency curve and allow the same percentage accuracy of measurement at any part of the scale. Since the ratio of maximum to minimum capacity is about 2 to 1, the frequency ratio for any coil used with the condenser is $\sqrt{2}$.

The coils used with this frequency meter are wound on Pyrex glass cylinders. The glass forms were chosen as giving greater constancy and stability than was obtainable with a skeleton-frame inductor. The inductors were wound with different sizes of wire, as selected from the data reported in a previous paper by the author.[1]

The frequency meter has been used by adjusting the condenser to resonance, as indicated by the maximum deflection of a direct current microammeter in a separate series circuit containing a crystal rectifier and small coil of two turns coupled to the coil of the frequency meter. Recently an improvement in the precision of setting was obtained by incorporating an arrangement used by a manufacturer of radio apparatus and standards in some special frequency meters. A very small condenser was built into the condenser shield so that the total capacity could be slightly increased by connecting the condenser into the circuit, which is accomplished by means of a spring push button. The main condenser is so adjusted that the deflection of the microammeter is the same with or without the small condenser in the circuit. When the frequency meter is correctly adjusted it is not quite in resonance with the generator, but set to a somewhat higher frequency. The calibration is based on this setting.

6. AUXILIARY APPARATUS

Among the auxiliary apparatus used in the measurements, the most useful has been a set of tuning forks ranging in frequency from 100 to 2,000 cycles. By matching a beat note with the note of a tuning fork, a known frequency difference can be produced, which

[1] B. S. Tech. Paper No. 330, "Resistance of Conductors of Various Types and Sizes as Windings of Single-Layer Coils at 150 to 6,000 Kilocycles." Obtainable from Superintendent of Documents, Government Printing Office, Washington, D. C., for 5 cents.

permits a simple calculation of a frequency which may be inconvenient to set precisely otherwise. Three electrically driven forks have been available, but the simple type of fork held in the hand and struck with a small mallet has been found more convenient.

A detector and 2-stage amplifier has been very useful. A small coil coupled to both the piezo oscillator and the power generator is at times connected to the input of the detector circuit in order to amplify the beat frequency. Other apparatus, such as another radio-frequency generator and a two-string oscillograph, is sometimes useful in making measurements.

IV. OPERATION OF APPARATUS

1. ADJUSTMENT OF 10 KC GENERATOR IN TERMS OF PIEZO OSCILLATOR STANDARD BY MEANS OF SPECIAL BEAT INDICATOR

The approximate setting of the 10 kc generator *G* (fig. 3) is first found by listening in telephones connected in the output of the amplifier *Q*, which is connected to the special beat indicator. After adjusting the 10 kc generator *G* to zero beat a rather faint high note may be heard, or, if the power generator *P* (fig. 3) is operating near some harmonic of the 10 kc generator, rapid pulsations in the beat note between the two generators may be heard. This renders it much easier to adjust the 10 kc generator correctly. By careful adjustment of the tuning control of the 10 kc generator, this high note will fluctuate in intensity, and when the fluctuation becomes slow enough the pointer of the milliammeter *A* will be found to vibrate in step with the fluctuation. By further adjustment of the tuning control of generator *G* the pointer can be kept from moving. At this point the 10 kc generator *G* can be shifted by further slight adjustment so that there is either a high-pitched faint note or absolute quiet. The latter condition occurs when the generator is correctly adjusted with respect to the frequency standard used. If the generator gets out of adjustment by as much as one cycle per second in a minute the operator will detect it by hearing the high-pitched note appear in the telephones. Slight errors in this setting may not be important unless a high harmonic is to be used. Errors in adjustment of the order of a few hundredths of a cycle per second are immediately apparent and the 10 kc generator can be readjusted. The milliammeter *A* is used only to indicate the desired adjustment between the frequency standard *S* and generator *G* and never indicates the adjustment of generator *P*. A second indicator might be used for this purpose, but has not been incorporated thus far because of the added complication of the circuits.

The sensitiveness of the visible beat indicator is shown by the fact that when the coils of an unshielded piezo oscillator and the 10 kc generator were coaxial and from 2 to 3 feet apart, visible beats of the beat-indicator milliammeter, *A* (fig. 3), were readily obtained. Type 201–A tubes were used in both the piezo oscillator and the 10 kc generator. The link circuit *L* and the 1-stage amplifier *T* were not used in this case. In other words, the coupling to the piezo oscillator *S* was extremely loose, which meant that there was no danger of the frequency of the piezo oscillator, which was used as the standard, being changed by the other circuits. Thus the beat-indicator system could not affect the frequency of the standard.

2. ADJUSTMENT OF POWER GENERATOR TO DESIRED FREQUENCY BY MEANS OF AUDIBLE CHARACTERISTICS OF BEAT INDICATOR

When the 10 kc generator *G* has been adjusted accurately, the next step is to adjust the power generator *P*, (fig. 3) to the desired harmonic of the 10 kc generator. The telephones in the 2-stage amplifier *Q*, (fig. 3) also serve to indicate the correct adjustment of the power generator *P*. When working at the higher frequencies in the broadcast band, beat frequencies which otherwise would not be heard are made audible by placing a pick-up coil connected in series with the telephone leads in the vicinity of the power generator *P*.

The frequencies of the power generator *P*, in which the last digit is zero, give a zero beat which can not be set accurately by aural methods without the use of another generator, because of the uncertainty of the setting for true zero beat. The frequencies ending in

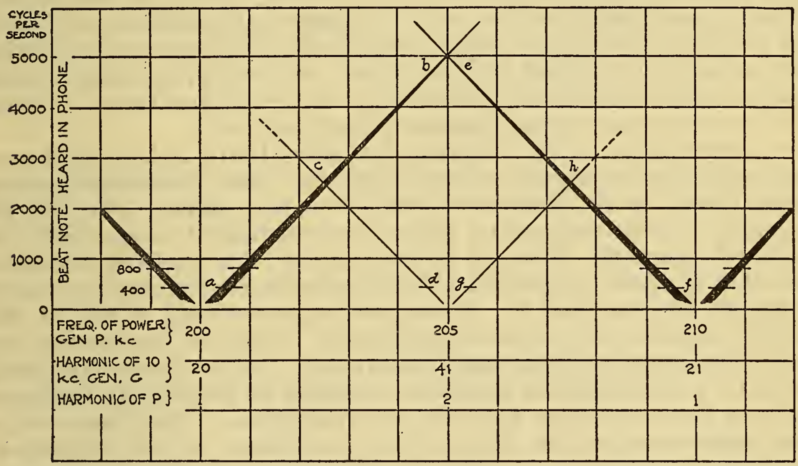

FIGURE 6.—*Chart used in explanation of the beat notes which are heard when working with the system described in the text*

2½, 5, and 7½ can be set accurately by matching beat notes in the telephone receivers, which are beats of beats, as described below.

Figure 6 illustrates how the various beat notes heard in the telephones can be interpreted; that is, whether the frequency to which the power generator *P* is set ends in zero or in some other number. The diagonal lines represent the beat notes heard in the telephones, and the breadth of the lines represents their relative strength. Thus it is seen that the beat notes occurring near the frequencies ending in zero are very loud or strong. Zero beat being indefinite, a setting is taken by matching with the note from a tuning fork, as described above. This method is simpler than providing an extra beat indicator to determine the desired frequency adjustment. When the frequency of the power generator *P* is increased from 200 kc, for example, as indicated in Figure 6, the beat note gradually gets higher and fainter, line *ab*, until at a frequency of the order of 204.5 kc the beat note is quite high, but a lower note, line *cd*, will also be heard, which becomes lower as the other becomes higher. Soon after the low note has become silent the high note will be heard to pulsate, and, with critical adjustment of the generator *P* beats with another beat note will be heard, which permit a very accurate setting of the generator. This setting gives one of the 5 kc points, and is readily distinguished over a range of several hundred kilocycles by the aural method described. If the frequency of the power generator is increased further, the other high frequency beat note, line *ef*, becomes lower and stronger, and a weaker beat note, line *gh*, becomes higher and fainter. Further change in the power generator brings in a loud beat note and, finally, silence, or zero beat, in the telephones. This is another 10 kc point. The beat note represented at *b* is 5,000 cycles when a 10 kc fundamental is used. When the frequency of the power generator is being changed from *a* to *b* if conditions are right, another beat note may be heard at *c* and a precise setting made at this point, which will be midway between the 10 kc point and the 5 kc point. This setting is more difficult to obtain than the 5 kc point because it is indicated by the beats between two 2,500-cycle notes of very different intensities. When a piezo oscillator having a fundamental frequency of 25 kc was used, the 2,500-cycle notes were readily distinguishable. Other beat notes may be heard and can be set accurately, but may not be readily usable because of the difficulty in identifying them. Points 5 kc apart are much closer than are usually required.

An explanation of the various beat notes heard in the telephones can be given by further reference to Figure 6, where harmonic numbers are indicated for the three zero-beat frequencies given. The 200 kc frequency or fundamental of the power generator *P* beats with the twentieth harmonic of the 10 kc generator *G*, and the 210 kc fundamental of the power generator *P* beats with the twenty-first harmonic of the 10 kc generator *G*. When the frequency used is 205 kc, the second harmonic of the power generator *P*, or 410 kc, beats with the forty-first harmonic of the 10 kc generator *G*. As previously explained, the 202.5 kc and 207.5 kc points are obtained by listening to the beats between the beat notes heard in the telephones. Beat notes other than those indicated in Figure 6 may be heard in the telephones, but those described are usually sufficient for calibration purposes.

Although the 10 kc points can not be set precisely, they can be accurately determined by matching a beat note in the telephones with a corresponding note from the tuning fork. If the frequency of the fork is known it is only necessary to make the measurement on one side of zero beat.

3. MEASUREMENT OF AUDIO-FREQUENCY NOTE RESULTING FROM DIFFERENCE IN FREQUENCY BETWEEN PIEZO OSCILLATOR UNDER TEST AND GENERATOR

The determination of the difference in frequency between the piezo oscillator under test *P O* and generator *P* (fig. 3) is made by matching with a similar note from an audio-frequency generator. While this matching would seem to be an easy matter, sometimes in practice it is found to be very difficult, either because the note is weak or many harmonics are present, or it is modulated with some other frequency, such as 60 cycles, when the power supply line of this frequency is used to operate the tube of the piezo oscillator *P O*.

When the two notes are nearly matched, slow beats will be heard when listening in the two telephone receivers which are connected to the piezo oscillator *PO* and the audio-frequency generator *AF*, respectively. Beats may also be heard when there is a small harmonic ratio between the frequencies. While it is convenient to have both notes coming from one headpiece when precise matching is desired, it is essential to be able to listen to each note separately during the process of adjustment, as, otherwise harmonics are very likely to be obtained.

4. MEASUREMENT OF AUDIO FREQUENCY WITH FREQUENCY METER

By means of the frequency meter *FM* (fig. 3) described in another section it is possible to check the results obtained with the audio-frequency generator *AF*. The check measurements involve two readings of the frequency meter *FM*, one when the generator *P* is adjusted to zero beat with the piezo oscillator *PO*, and the second when the generator *P* is adjusted in terms of the frequency standard *S*, by means of amplifier T, 10 kc generator *G*, and the special beat-indicator circuits as described above. The difference in the two readings of the frequency meter *FM* should give a result approximately the same as that obtained with the audio-frequency generator *AF*, and thus serves as a check on those measurements.

V. TEST PROCEDURE

In starting the test of a piezo oscillator, it is set up on a small portable table, and tried out using the type of tubes and voltages specified. A number of preliminary measurements are made as described below, including test for fundamental frequency, which is only a very approximate measurement, test to determine this frequency value within 1 or 2 kc, and test to discover any undesired frequencies. The apparatus used for these tests consists of the usual type of frequency meter and radio-frequency generator rather than the more complicated equipment described in this paper.

The fundamental frequency of the piezo oscillator is determined approximately by coupling a frequency meter to the oscillator and noting the setting at which the reading of the meter in the plate circuit of the piezo oscillator increases. If the coupling is too close, the piezo oscillator will stop oscillating, in which case the meter in the plate circuit will read the normal plate current of the tube. The coupling can readily be adjusted so that a momentary increase in the reading of the meter may be noted as the frequency meter passes through the fundamental frequency of the piezo oscillator In general, this coupling is such that no response will be obtained at a harmonic, and, therefore, the method may be relied upon to give the fundamental frequency within 1 or 2 per cent.

After the fundamental frequency has thus been determined roughly, a more precise determination is made, which may be of the order of 0.2 per cent. This measurement is made by setting a small radio-frequency generator to zero beat with the piezo oscillator and measuring the frequency of the generator with a suitable frequency meter.

It is essential that a quartz plate which is to be used as a frequency standard have but one frequency at which it operates when circuit constants are not appreciably changed. One of the important tests upon a piezo oscillator, therefore, is that to determine whether the quartz plate may operate at a slightly different frequency than the one desired. Quartz plates are often found to have two or more frequencies separated a few hundred cycles. Such undesired fre-

84789°—29——9

quencies can often be found by setting a radio-frequency generator so that a certain audio-frequency note is produced in the telephone receivers in the piezo oscillator circuit. Changes are then made in the various adjustments of the piezo oscillator, and the quartz plate is turned from side to side. If the beat note suddenly changes to some other pitch, the quartz plate is operating at a different frequency, and will not be satisfactory as a standard. A gradual change in frequency is to be expected if, for example, the condenser setting of the piezo oscillator is varied. If the piezo oscillator appears to operate satisfactorily, it is wheeled into the room where the temperature is maintained constant 24 hours in the day. If the quartz plate requires grinding to bring it to the desired frequency, this work is done before the tests outlined above are made, and then the piezo oscillator is placed in the special room. The above tests complete the preliminary measurements.

The piezo oscillator remains in the constant-temperature room over night, and the first precision measurement of its frequency is made the following day. On the next day the precision measurements are repeated, and if the frequency measured is sufficiently close to the value of the previous day, the piezo oscillator is again tested for two frequencies or other peculiarities in operation, and if found to be satisfactory, is returned to the owner, and a test certificate prepared. However, if the measurements of the second day do not agree with those of the first day, the piezo oscillator is kept over and tried a third time, and efforts made to determine the cause of the disagreement in the measurements. Certificates are not issued for quartz plates which operate in an erratic manner.

If the piezo oscillator is to be tested at a given temperature, the temperature-controlled cabinet must be submitted with the piezo oscillator. The complete equipment is set up, and readings of the temperature near the quartz plate are noted at intervals until a constant temperature is obtained or until the limits within which the device operates are found. If the device is satisfactory in operation, the first precision frequency measurement may be made after the piezo oscillator has been at the required temperature at least 24 hours. The remainder of the test is conducted as has previously been described.

Figure 7 gives a view of the apparatus used in the constant-temperature room.

TABLE 1.—*Measurement of 1,370 kc piezo oscillator.*

[Values in kc]

Setting of generator *P*	Piezo oscillator under test	Generator *P* fundamental frequency	Frequency meter *FM*	Second harmonic	Audio generator *AF*
Zero beat with piezo oscillator under test	±1, 370	±685	685. 12	1, 370. 24	
Zero beat with standard		685. 000	685. 00	1, 370. 00	0. 193
Frequency of piezo oscillator is 1,370.000+0.193=1,370.193 kc				0. 24	

Table 1 shows data taken on a piezo oscillator for 1,370 kc. Reading from left to right, zero beat with the piezo oscillator at about 1,370 kc is taken by setting the generator *P* to half this frequency, or approximately 685 kc. Reading the frequency of the generator *P*

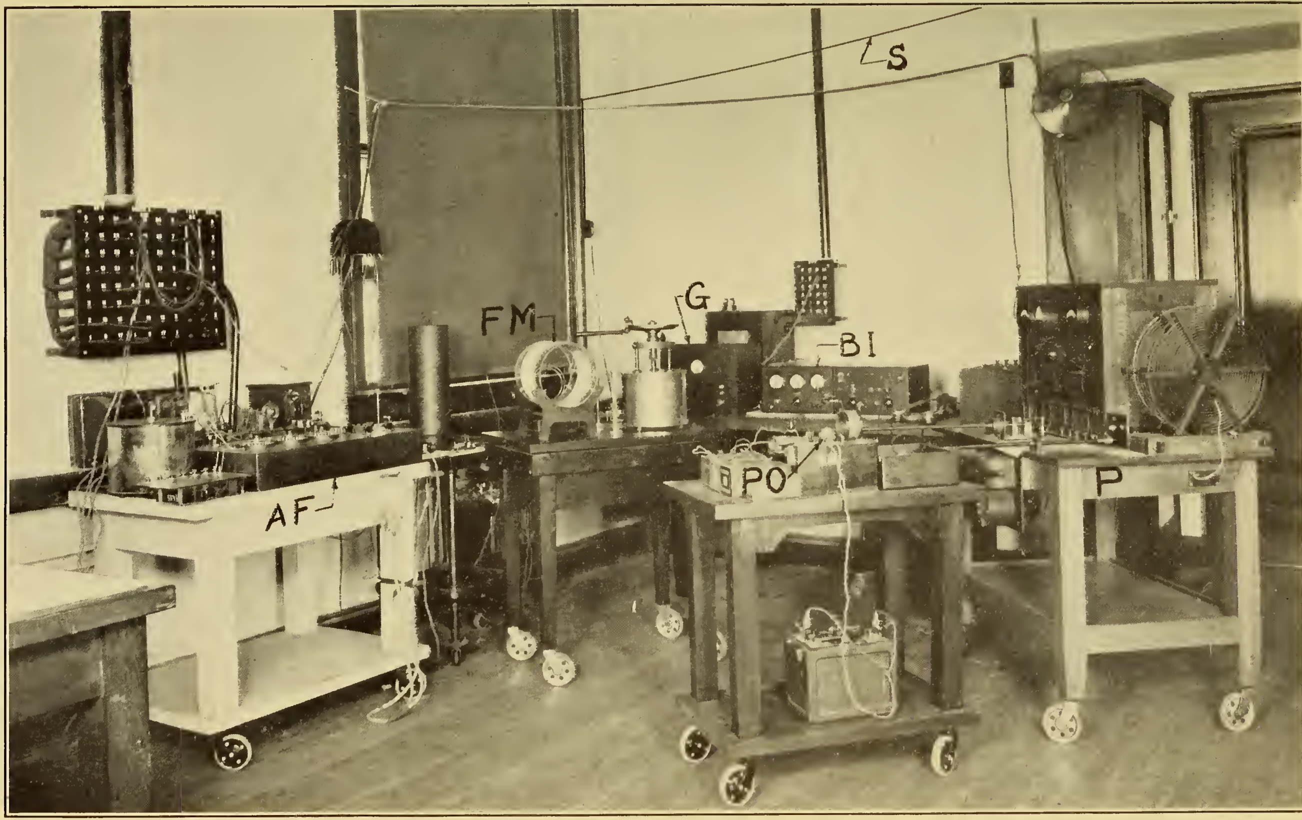

Figure 7.—*Apparatus used in testing piezo oscillators*

S, Wires leading from 200 kc standard; *G*, 10 kc generator; *BI*, special beat indicator; *P*, radio-frequency generator; *PO*, piezo oscillator under test; *FM*, frequency meter; *AF*, audio-frequency generator.

with the frequency meter *FM*, 685.12 kc is obtained, giving 1,370.24 kc for the fundamental frequency in terms of the frequency meter. In the second part of the measurement, zero beat is obtained with the standard, for which condition the generator *P* is set at 685.000 kc and the frequency meter *FM* indicates 685.00 kc, for which the second harmonic is 1,370.00 kc. The beat note between the piezo oscillator under test and the generator *P* is matched by comparison with the audio-frequency generator *AF* and a value of 0.193 kc obtained. It will be noticed that this value is in fair agreement with the difference obtained from the values in the "second harmonic" column. As the values in the latter column are twice the readings obtained from the frequency meter, the errors in the calibration of the latter are doubled. When this fact is considered, it will be apparent that the frequency-meter calibration was quite satisfactory. It will be noted that the frequency meter reading for zero beat with the piezo oscillator gave a higher frequency than for zero beat with the standard. The value, 0.193 kc, should, therefore, be added to 1,370.000 kc, giving 1,370.193 as the frequency of the piezo oscillator under test. The piezo oscillator probably will not hold its frequency to better than 0.01 per cent so that the value may be reported as 1,370.2 kc. The frequency meter readings are used only as a guide, or check, on the accuracy of the more precise measurements based on beat frequencies.

An interesting point may be noted here. In the above paragraph it is evident that the error in the frequency meter calibration is multiplied or increased when the frequency used in the test is a fractional value of the fundamental of the piezo oscillator. Conversely the error in the frequency meter calibration is divided or reduced when the frequency used in the test is a harmonic of the fundamental of the piezo oscillator. If an attempt is made to gain this advantage of the reduction in the error of the frequency meter measurement in the case of broadcast frequency testing, other difficulties may more than offset it. It may, however, be applied with considerable success in the measurement of the frequency of quartz plates having a low frequency fundamental, and the possible error in the frequency meter calibration may be reduced to a small amount.

If the frequency of the piezo oscillator is within 50 or 100 cycles of being correct, it is convenient to change the second step in the measurement so that the generator *P* is set off the desired frequency by a known amount, which can be readily accomplished by matching the beat note in the standard circuits with the note from a tuning fork. Table 2 shows results obtained in such a test.

TABLE 2.—*Measurement of 940 kc piezo oscillator*

[Values in kc]

Setting of generator *P*	Piezo oscillator under test	Generator *P* fundamental frequency	Frequency meter *FM*	Second harmonic	Audio generator *AF*
Zero beat with piezo oscillator under test	±940	±470	469.99	939.98	
Generator *P* set off from standard using tuning fork		470.000−0.400=469.000	469.55	939.10	0.833
Frequency of piezo oscillator is 469.6×2+0.833=940.033 kc				0.88	

The first part of the measurement is made in a similar manner to that given for Table 1. In the second part of the measurement if zero beat is obtained with the standard as in Table 1, the beat note with the piezo oscillator would be too low to hear. The generator *P* is therefore set off from zero beat by matching the note between the generator *P* and the standard with a 400-cycle tuning fork, which gives 469.600 kc as the generator frequency. According to the frequency meter *FM*, it is set at 469.55 kc with a second harmonic of 939.10 kc. The beat note between the generator *P* and the piezo oscillator *PO* is matched with a corresponding note from the audio-frequency generator *AF* which gives a reading of 0.833 kc. It will be noted that the difference in the two frequency meter readings gives 0.88 kc, which indicates that no error from harmonics has been introduced. The frequency of the piezo oscillator *PO* is therefore measured as 940.033 kc, which will be reported as 940.0 kc.

VI. CONCLUSION

While the method of test described has had reference to the testing of piezo oscillators, the system is likewise applicable to the measurement of the frequency of a transmitting station, or the calibration of a frequency meter. The latter application of the system has been described in the author's paper mentioned on page 118. In the case of the measurement of the frequency of a radio station, the piezo oscillator under test above would be replaced by a radio receiving set tuned to the station whose frequency is to be measured.

The method described is a precise method, and its precision can be increased further by the use of an oscillograph. It is capable of adequate accuracy for any apparatus to be tested.

The system has the following advantages: (1) great accuracy, (2) high precision, (3) use of a given standard over a wide range, (4) large number of calibration points available, (5) flexibility of system, and (6) ease of operation.

1. Great accuracy is possible with the system and method used because all measurements are based upon a temperature-controlled piezo oscillator, and the final frequency value is in terms of the standard and an audio-frequency generator which holds its calibration over long periods without appreciable change.

2. High precision is obtained in the measurements because of the fact that beat notes are used in making the various adjustments.

3. The usefulness of a given piezo oscillator used as the standard may be greatly extended by reason of the many harmonics which are available from the system as a whole.

4. The many calibration points available come from the harmonics spaced 5 kc apart and the use of tuning-fork notes to displace the setting an accurately known amount.

5. The method is flexible in that it can be adapted to many kinds of frequency measurements, including those on piezo oscillators, radio stations, and frequency meters.

6. The system is quite simple to operate when the accuracy and large number of points obtainable are considered.

In conclusion, by means of the method and apparatus described, results of high accuracy are obtained in relatively short time in the testing of piezo oscillators for broadcasting stations.

WASHINGTON, August 15, 1929