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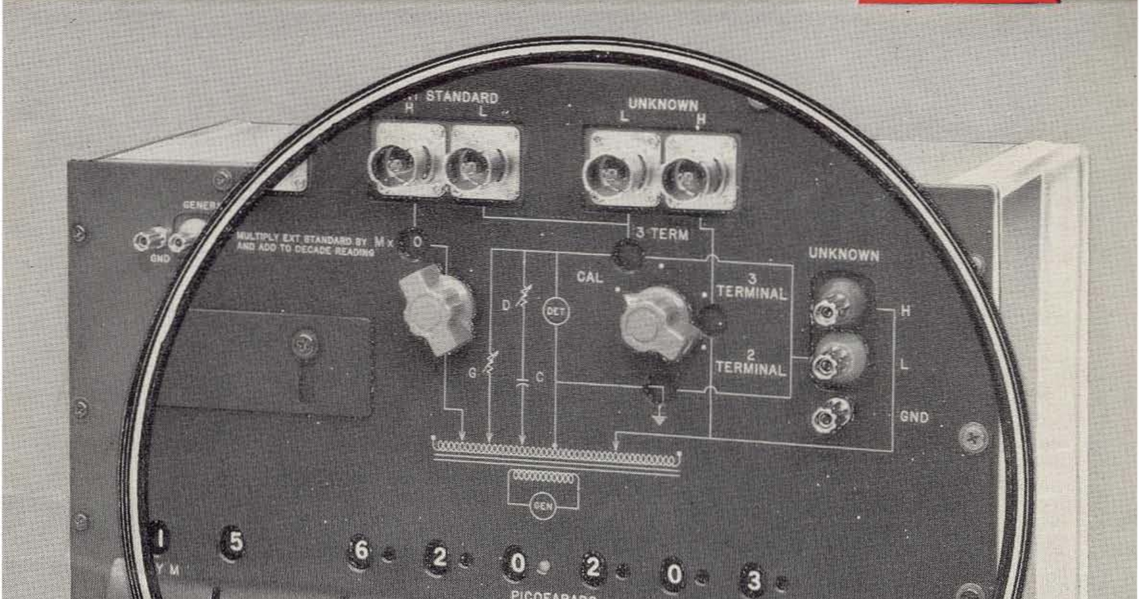

VOLUME 36 Nos. 8 & 9 AUGUST—SEPTEMBER, 1962

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Capacitance Bridge
Audio Oscillator
Coaxial Cable Connectors
1962 EIME Schedule

THE GENERAL RADIO

EXPERIMENTER

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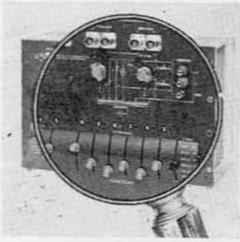

Lever-type switches and digital readout on the Type 1615-A Capacitance Bridge bring a new order of convenience to capacitance measurements. This new bridge has an accuracy of 0.01% and a resolution of one part in a million.

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ACCURACY, PRECISION, AND CONVENIENCE FOR CAPACITANCE MEASUREMENTS

The direct-reading accuracy of 0.01% in the new Type 1615-A Capacitance Bridge here being introduced is an improvement of an order of magnitude in accuracy over most preceding bridges. This has been made possible by the improvements introduced in recent years in standards of absolute capacitance, in capacitance bridges, and in reference capacitors at the National Bureau of Standards[1] and other standards laboratories. The computable cross capacitor developed at the National Standards Laboratory of Australia by Thompson and Lampard[2] has made it possible to determine the unit of capacitance with an accuracy that is now a few parts per million and which may be expected to improve. The advantages of ratio transformers and of transformer ratio arms in bridges, exploited initially in Great Britain and then more fully in Australia, have been utilized to increase the precision of measurement and to extend the range to capacitances below 1 micro-picofarad (10^{-18} farad). Furthermore, the reference capacitors used to store and transfer the capacitance unit have

[1] M. C. McGregor, J. F. Hersh, R. D. Cutkosky, F. K. Harris, and F. R. Kotter, "New apparatus at the National Bureau of Standards for absolute capacitance measurement," *IRE Trans. on Instrumentation*, vol. I-7, pp 253–261; December, 1958.

[2] A. M. Thompson, and D. G. Lampard, "A New Theorem in Electrostatics and its Application to Calculable Standards of Capacitance," *Nature*, 177, 888 (1956).

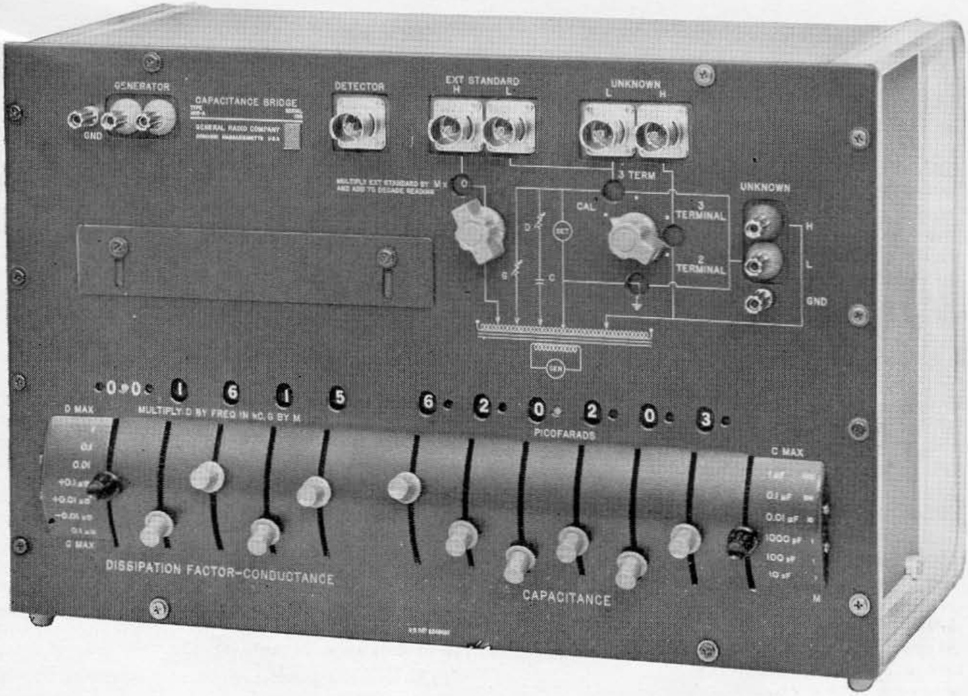


Figure 1. Panel view of the Type 1615-A Capacitance Bridge.

been improved by the use of three-terminal construction to minimize connection errors, which limit accuracy in capacitors of 1000 pf or less,[3] and by the use of new construction methods, low-temperature-coefficient materials, and sealed containers to increase the stability. With this new apparatus, the National Bureau of Standards can now certify capacitors to an accuracy of 50 ppm or better.

Many of these improvements have also been incorporated into the new TYPE 1615-A Capacitance Bridge. This bridge has transformer ratio arms for accuracy and stability. Its internal capacitance standards are three-terminal, sealed capacitors having low temperature coefficients. The bridge has six-figure resolution for capacitance from 1 μf to 1 pf and a direct-reading accuracy of 0.01% over this capacitance range and over most of the frequency range from 100 cycles to 10 kc. The impedance of the transformer ratio arms has been kept very low, so that accurate three-terminal measurements can be made even in the presence of large capacitances to ground. The bridge also has the necessary internal shielding to permit one terminal of the unknown to be grounded, so that both two-terminal and three-terminal measurements can be made over the whole capacitance range.

The balance controls are lever-type switches, the readout is digital, and the decimal point is automatically positioned.

These features, and others described below, result in a capacitance bridge that brings to the measurement of capacitance, to the intercomparison of standards, and to the measurement of dielectric properties an unusual degree of accuracy, precision, range, and convenience.

TRANSFORMER RATIO ARMS

Many of the advantages of inductively coupled, or transformer, ratio arms have been known since about 1888, and they are covered in detail in the 1928 British patent of A. D. Blumlein. Little use was made of them, however, until about the time of World War II, when new applications were found in the measurement of very small capacitance. Since that time, transformer ratio arms have become increasingly popular in commercial bridges as well as in the apparatus of the national standards laboratories.

The advantages of such ratio arms are that accuracies within a few parts per million are not difficult to obtain over a wide range of integral values, even for ratios as high as 1000 to 1, and that these ratios are almost unaffected by age, temperature, or voltage. The low impedance of the transformer ratio arm also makes it easy to measure direct impedances and to exclude the ground impedances in a three-terminal measurement without the use of guard circuits and auxiliary balances.

To illustrate these characteristics, a simple capacitance bridge with transformer ratio arms is shown in Figure 2. On the toroidal core, a primary winding, connected to the generator, serves only to excite the core; the number of primary turns, N_P, determines the load on the generator but does not influence the bridge network. If all the magnetic flux is confined to the core—as it is to a high degree in a symmetrically wound toroid with a high-permeability core—the ratio of the open-circuit voltages induced in the two secondary windings must be exactly equal to the ratio of the number of turns. The ratio can be changed by the use of taps along the two secondaries, but, when the number of turns is fixed, the voltage is highly invariant. Changes in the core permeability with time and temperature have only second-order effects on the ratio, because they modify only the very small amount of leakage flux that is not confined to the core in a practical transformer. The ratio is, therefore, both highly accurate and highly stable.

In Figure 2, the two transformer secondary windings are used as the ratio arms of the capacitance bridge with the standard capacitor, C_N, and the unknown, C_X, as the other two arms in a conventional four-arm bridge network. The condition for balance or zero detector current is easily shown to be that $V_N C_N = V_X C_X$ or $C_X/C_N = V_N/V_X = N_N/N_X$. This balance condition is not affected by the capacitances shown from the H and L terminals of C_N and C_X to the terminal G connected to

[3] J. F. Hersh, "A Close Look at Connection Errors in Capacitance Measurements," *General Radio Experimenter*, 33, 7, July, 1959.

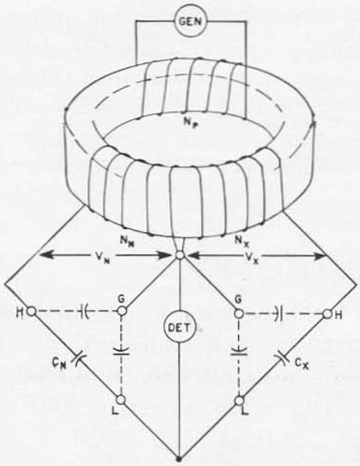


Figure 2. A capacitance bridge with transformer ratio arms.

the junction of the ratio arms. The capacitances between L and G shunt the detector, so that they affect only the bridge sensitivity. The capacitances between H and G are across the transformer windings. To the extent that the transformer can be assumed ideal, i.e., with no resistance in the secondary windings and with no flux that does not link equally both secondaries, the current drawn by the H-G capacitances does not change the voltages V_N and V_X or the balance conditions. In practice, the transformer resistances and leakage inductances can be kept so small that quite low impedances or large capacitances can be connected from H to G before there is appreciable error in the bridge.

The junction of the ratio arms, G, is therefore a guard point or guard potential in the bridge. All capacitances to G from the H or L corners of the bridge are excluded from the measurement. In the three-terminal capacitors represented by the H, L, G terminals in Figure 2, the bridge measures only the direct capacitance, C_X, of the unknown in terms of the direct capacitance, C_N, of a standard, without additional guard circuits or balances.

One can take advantage of the accurate and stable ratios of the transformer by the use in the bridge of a standard arm which is fixed and a ratio which can be varied to balance the bridge.

Figure 3 shows three of the possible ways of balancing a simple transformer-ratio capacitance bridge. For simplicity, the generator and primary are not shown, but it is assumed that the two secondaries have 100 turns each and are excited so that there is 1 volt per turn. The capacitor in the unknown arm is assumed to be 72 picofarads.

In Figure 3a, the two ratio arms are equal and the bridge is balanced in the conventional way with a variable standard capacitor which is adjusted to 72 pf.

The detector current can equally well be adjusted by a variation in the voltage applied to a fixed standard capacitor. In Figure 3b, the standard capacitor is fixed at 100 pf, and this is balanced against the 72-pf unknown connected to the 100-volt end of the transformer by connection of the standard to 72 volts of the opposite phase, obtained from suitable taps on the transformer windings. The inductive divider shown has a winding of 100 turns with taps every 10 turns and, on the same core, another winding of 10 turns tapped every turn. If, as shown, the second winding is connected to the 70-volt tap on the first winding and the capacitor to the 2-volt tap on the second winding, the required 72 volts is applied to the capacitor. Six or more decades for high precision can be obtained in a similar fashion with more turns on one core and the use of additional cores driven from the first. Such inductive dividers have very accurate and stable ratios, but the errors increase with the number of decades because of loading effects.

Another method of balance by voltage variation is shown in Figure 3c, where a single decade divider is used in combination with multiple fixed capacitors. The 100-turn secondary is tapped every 10 turns to provide 10-volt increments. If, then, a 100-pf capacitor is connected to the 70-volt tap and a 10-pf capacitor to the 20-volt tap, the resulting detector current balances that of the 72-pf unknown connected to 100 volts. This bridge can be given six-figure resolution, for example, through the use of six fixed capacitors in decade steps from 100 pf to 0.001 pf, each of which can be connected to any one of the taps on the transformer.

In any of these bridges, the bridge ratio can also be varied by use of taps on the unknown side of the transformer to vary the voltage applied to the unknown capacitor. For example, if the unknown capacitor were connected to a 10-turn or 10-volt tap on the upper half of the transformer, then a capacitance of 720 pf instead of 72 would be balanced by the standard capacitors shown. The range of the bridge can thus be extended to measure capacitors which are much larger than the standards in the bridge.

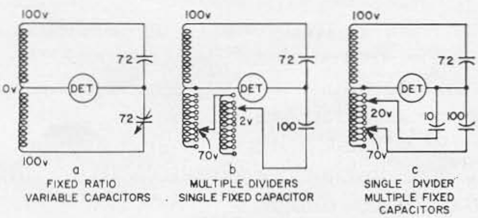


Figure 3. Methods of balancing capacitance in a transformer-ratio bridge.

These advantages of transformer ratio arms and dividers make possible a bridge of very wide range and high accuracy, since not only are the ratios stable and accurate but, when only a few fixed capacitors are required as standards, the standards can be constructed to have high stability and accuracy. This bridge can also have a wide range of frequencies. At low frequencies, a limit is imposed on sensitivity by the maximum voltage obtainable from the transformer, since, for a given core, the voltage at saturation is proportional to frequency. At high frequencies there is a decrease in accuracy resulting from the decrease in core permeability with frequency, from the increased loading of the transformer by its self-capacitance as well as the bridge capacitances and, of course, from the usual residual capacitances and inductances in the bridge wiring and components.

THE TYPE 1615-A CAPACITANCE BRIDGE

CAPACITANCE

The new Type 1615-A Capacitance Bridge is a transformer-ratio bridge of the type that uses a single decade of transformer voltage division and multiple, fixed, standard capacitors to provide six decades of resolution in capacitance. As shown in the elementary diagram of Figure 4, one side of the secondary of the ratio transformer is tapped at intervals of one-tenth, and to these taps can be connected six standard capacitors in any combination required to balance the bridge. If, for example, the standards connected to the six-decades switch are 1000, 100, 10, 1, 0.1, and 0.01 pf, the range of unknown that can be balanced is from 1000 pf to 0.001 pf when the unknown is connected to the full voltage of the other secondary of the transformer. This unknown side of the transformer has, however, a tap at one-tenth of the full voltage, so that when the unknown is driven from this lower voltage, the range is multiplied by ten, and an unknown up to 10,000 pf or 0.01 μf can be balanced by the same internal standards. The range is extended still further by further division of voltage on the unknown side through a second transformer or inductive divider driven from the 0.1 tap on the ratio transformer. This second divider provides additional ratios of 0.1 and 0.01, so that, with the voltage applied to the unknown reduced to 0.01 and 0.001, the bridge is given two more ranges of 0.1-μf and 1-μf maximum capacitance.

To extend the range to smaller capacitances, two additional standards are used, of 0.001 and 0.0001 pf. This yields two more ranges, 0.0001 pf to 100 pf and 0.00001 pf to 10 pf. There are, therefore, eight standard capacitors, only six of which are used for any one range. The connections of these capacitors are made by the same range switch that selects the transformer taps.

With this combination of eight internal standard capacitors and four voltage ratios to which the unknown can be connected, the capacitance range of the bridge extends from a maximum of 1.111,110 μf to a minimum step of 0.00001 pf or 10^{-11} μf. The capacitors and ratios used for each range are indicated in Figure 5.

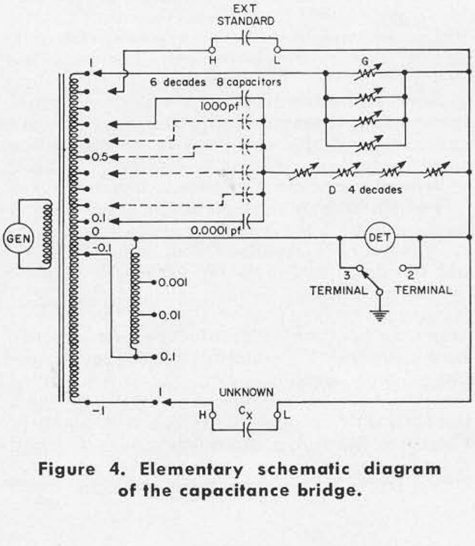


Figure 4. Elementary schematic diagram of the capacitance bridge.

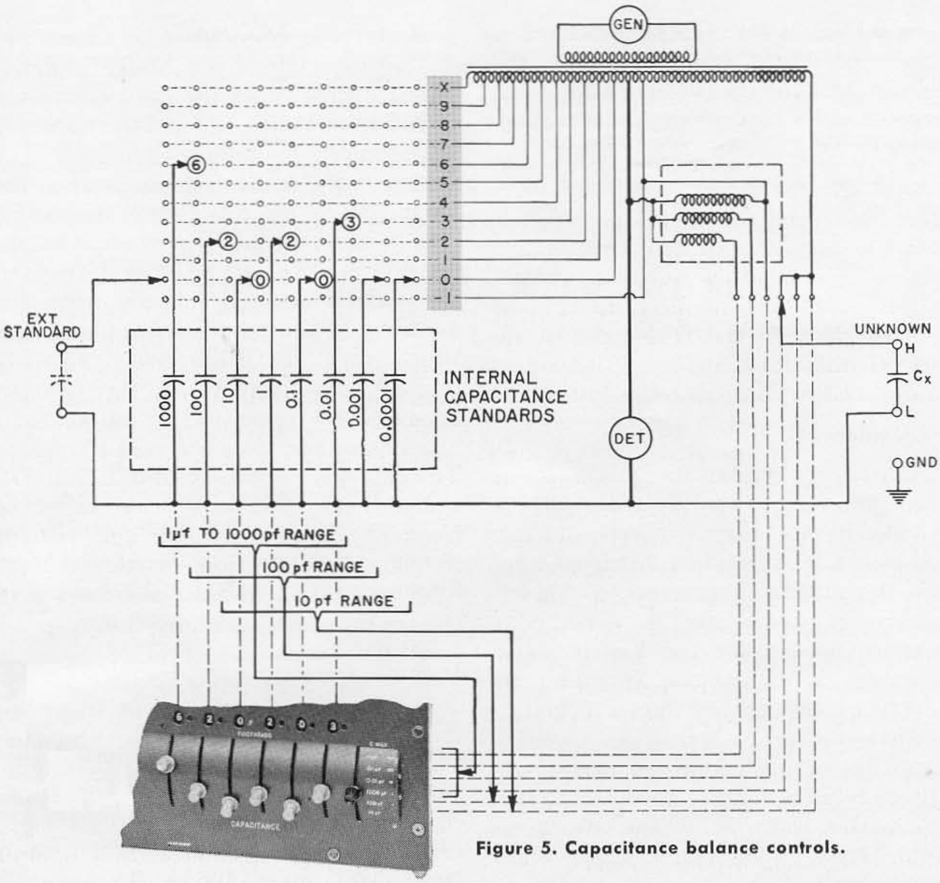


Figure 5. Capacitance balance controls.

LOSS

To obtain a precision of six figures in the capacitance balance, the loss balance must be made equally precise. As shown in Figure 4, the loss balance in this bridge can be made in terms of either the dissipation factor, D, or the shunt conductance, G, of the unknown. For most purposes, dissipation factor offers the greater range and convenience. Conductance is useful in some measurements of dielectric materials and is necessary when external standards are added to the bridge and when the loss in the bridge standards exceeds that of the capacitor being measured.

Dissipation Factor

The dissipation-factor balance is made by means of four resistance decades connected in series with the common side of all the internal capacitance standards as shown in Figure 4. Since $D = \omega R C_T$, where C_T is the total capacitance connected to the junction of the capacitors and resistors, the resistance decades can be calibrated to read D directly at a particular frequency, in this case at 1000 cps. With four decades of 100, 10, 1, and 0.1 ohms per step and with the total capacitance adjusted to 0.001592 μf, the range of D at 1000 cps is from 0.01 to 0.000001. At other frequencies, the indicated D must be multiplied by the frequency in kilocycles. To extend the range to higher D, additional capacitors are added by a range switch to make C_T = 0.01592 μf for a maximum D of 0.1 and to make

$C_T = 0.1592$ μf for a maximum D of 1. This capacitance added between the resistors and the transformer end of the detector does not change the capacitance balance.

Although the bridge has only four-figure resolution in D, this precision is adequate for the six-figure capacitance balance of capacitors whose D is 0.01 or less, since the smallest division of the 0.01 range of the D decades is one part per million.

Conductance, G

Balance of loss in the unknown in terms of shunt conductance, G, is provided in this bridge by the equivalent of four decades of conductance in parallel with the internal capacitors, as shown figuratively in Figure 4. The conductance needed for the loss in most capacitors is small, corresponding to resistance much greater than a megohm, so that ordinary resistance decades cannot be simply connected across the capacitors. It is simple, however, to use resistance decades in a T network to obtain a variable conductance. With 100-kilohm resistors as the series arms and the same four resistance decades used for D as the shunt arm, the range of G is from 0.1 μmho to 0.00001 μmho. The conductance is reduced by a factor of ten when the network is switched to the 0.1 tap on the transformer instead of to the full winding, and the range is then from 0.01 to 0.000001 μmho. When the loss in the external or internal capacitors exceeds that of the unknown, the bridge must be able to add loss to the unknown. With the conductance balance of loss, the T network can be readily switched to the taps at full or tenth voltage on the unknown side of the bridge to provide the same two ranges of conductance across the unknown $(-G)$ as there are for conductance across the internal and external standards $(+G)$.

ACCURACY

The accuracy of the bridge is determined primarily by the accuracy of the transformer ratios and by the accuracy of the internal standard capacitors. The accuracy of the ratios depends upon the magnitude of the ratio, upon frequency, and upon the load connected to the transformer. The accuracy of the capacitors, which depends initially upon the accuracy of the reference standard with which they are calibrated, is usually limited subsequently by the changes produced by aging and by fluctuations in temperature, pressure, and humidity. To achieve an accuracy of 0.01% in the bridge reading over a wide range of frequency and capacitance and without frequent recalibration, particular care has been taken in the construction of the transformers and capacitors.

Transformers

Relatively low numbers of turns are used in the transformers to keep the leakage inductance, stray capacitance, and resistances of the windings so small that the ratio accuracy remains high, even with loads greater than 1 μf and frequencies above 10 kc. These small residual impedances make it possible, for example, when a 1000-pf capacitor is being measured at 1000 cps with unity ratio, to load the transformer with as much as 1 μf of ground or cable capacitance before the error in the measured direct capacitance exceeds 0.01%. The small bridge inductances are not insignificant, however, when high capacitance is measured at high frequency, and the bridge error is then of the order of $+0.002\%\ C_{\mu f}\left(\frac{f}{1000}\right)^2$, if no correction for the inductance is used.

The accuracy of the ratios when the transformer is lightly loaded is better than 0.1 part per million for the unity ratio and is better than 2 ppm for the 0.1 ratio at 1000 cps or lower frequencies.

The winding self-capacitances act as a load as frequency increases, so that the error in the 0.1 ratio increases to about 20 ppm at 10 kc and to 0.2% at 100 kc. When the auxiliary transformer is connected for ratios of 0.01 and 0.001, the ratio errors are increased by the loading effects of the input impedance of the auxiliary transformer. These errors can, however, to a large extent be eliminated by compensating impedances, and the 0.01 and 0.001 ratios in the bridge are adjusted to within ±20 ppm in the frequency range below 10 kc. The phase errors are, in general, somewhat larger than the magnitude errors of the ratios. At 1000 cps, the phase error is probably within ±10 μradians, but the error increases in approximate proportion to ratio and to the square of frequency.

Capacitors

The internal standard capacitors are constructed to have such small changes with time, temperature, and environment that the initial calibration to ±0.01% may be expected to change less than 0.01% per year in normal use. The temperature coefficients of the 1000-, 100-, and 10-pf units, which are Invar multiple-plate capacitors, are less than 5 ppm/°C; the coefficients of the Invar Zichner-type 1-, 0.1-, and 0.01-pf units and of the cylindrical 0.001- and 0.0001-pf units are less than 20 ppm/°C.

For almost zero changes of capacitance with atmospheric pressure and humidity, all but the two smallest capacitors are hermetically sealed in an atmosphere of dry nitrogen. This sealing is necessary where stability of better than 0.01% is expected, because in an unsealed capacitor the capacitance changes about 2 ppm for each 1% change in relative humidity; hence a 50% change in humidity produces a 0.01% change in capacitance. And the pressure change, for example, resulting from moving the capacitor from the near-sea-level altitude of Washington, D.C., to the more than 5000-ft altitude of Boulder, Colorado, produces a capacitance decrease of about 0.01%.

To minimize long-term drift, all metal parts of the capacitors are Invar to avoid differential stresses, and they are annealed and temperature-cycled to relieve strains and to accelerate the initial aging.

The bridge can be calibrated quickly and accurately by the measurement of a single calibrated external standard capacitor of almost any size within the range of the bridge. Since the six-figure resolution of the bridge permits comparison with a precision better than 0.01% down to 1 pf, the accuracy of calibration is usually determined by the accuracy of the standard. Only one external standard, most conveniently a three-terminal 1000-pf standard,* is required because the accurate, internal 0.1 transformer ratio can be used to insure an accurate ratio of the internal capacitance standards. A −1 position on each capacitance lever switch connects the corresponding internal capacitor to the 0.1 tap on the unknown side of the transformer. This capacitor can be compared with the next decade capacitor, which is connected to the maximum voltage on the standard side when the adjacent lever is set on the x position, and any adjustments required can be made with trimmers accessible beneath a sliding cover on the bridge panel.

Such checks or recalibrations of the bridge need not be made often.

Loss

Although the accuracy of the measurement of loss is not important in the measurement of many capacitors, the Type 1615-A Capacitance Bridge makes possible measurements of dissipation factor to an accuracy which exceeds

*The Type 1404 Reference Standard Capacitors are recommended. These will be described in a subsequent issue.

that of most capacitance bridges. This accuracy of (±0.1% + 10 ppm) of the measured value is applicable over the whole D range and over nearly all the capacitance and frequency ranges. At low frequencies and small capacitance the accuracy will be limited by the reduced sensitivity of the bridge. At high frequencies and at ratios other than unity, the phase errors of the transformers will reduce the accuracy. Within these extremes, the accuracy of the D reading is determined by the resistance decades, which are adjusted within ±0.05%, and by the total capacitance connected to the decades, which is trimmed to adjust the D reading to within ±0.1% when a standard of known D is measured.

The loss measurement in terms of shunt conductance, G, is limited to an accuracy of ±(1% + 0.00001 μmho) by the accuracy of the 100-kilohm resistors used in the T network. Higher accuracy is seldom needed. It would not only add to the cost but would also require corrections to the bridge G reading. These corrections, amounting to a maximum of 2%, are due to the nonlinear relation between the decade resistance and the equivalent conductance of the network.

The loss measured by the bridge as either D or G is the loss of the unknown capacitor relative to the loss of the internal standards. Since the bridge capacitors are carefully cleaned and sealed in dry nitrogen, it is estimated that their dissipation factor does not exceed a few parts per million. The accuracy of absolute loss measured by the bridge is, therefore, the same as that of the loss relative to the bridge capacitors.

CONVENIENCE

Readout and Balance (Refer to Figure 1.)

Past experience leads many of us to picture a bridge of very high precision and accuracy as a massive but delicate laboratory instrument which, when handled with considerable care, coddling and some cunning, may yield an accurate value for capacitance only after the application of numerous corrections. The Type 1615-A Capacitance Bridge in no way fits this picture. The moderate size and weight of this bridge permit it to be moved about the laboratory with ease, and the bridge is sufficiently rugged to be transported into the field should its accuracy be required there. It is easy to balance, easy to read, and the reading is accurate without corrections.

A feature which contributes much to the ease of balance and of reading is the use of lever or linear rather than rotary switches for the decades. The small panel space occupied by these switches makes it possible to position the six decades and range switch for capacitance and the four decades and range switch for loss within the span of the operator's right and left hands, respectively. The throw of the switches is about three inches, so the 12-position range of any decade can be covered with only a slight motion of hand or finger.

The position of each decade is indicated by a number appearing in the window above each lever. The bridge capacitance readout thus appears in the convenient form of six closely-spaced digits in a horizontal line and the D or G readout as a similar line of four digits. As the lever at the right is moved to change capacitance range, the decimal point is automatically positioned in the six-figure readout to indicate without multipliers the capacitance in picofarads from a maximum of 1,111,110 pf to a minimum of 0.00001 pf. The lever on the left similarly moves the decimal point when the D range is changed to indicate directly the dissipation factor. The decimal point is also positioned automatically to read conductance in micromhos, but since G

must be multiplied by the factor M, this factor is indicated in orange engraving adjacent to each position of the C MAX range switch lever. This multiplier is required only for G and for external standards, and the orange color is used on the panel to indicate all quantities to which M must be applied.

Bridges of high precision are often reputed to be bridges which are not easily balanced. In spite of its wide range and high precision, the TYPE 1615-A Capacitance Bridge can often be balanced with more ease and speed than bridges of lower range and accuracy. For example, when even the approximate magnitude of a capacitor is not known, a rough balance can be made quickly on this bridge by the use of the maximum capacitance range, so that the six decades cover the range from 1 μf to 1 pf and the six levers can be tried in quick succession to determine the balance point without a change in range. The —1 position on each of the capacitance decades, which was mentioned above as useful in the self-calibration of the bridge, also facilitates balance in the region near any zero by permitting a trial reduction of bridge capacitance by one step in a decade without the necessity of moving the adjacent lever.

Connection of Unknown

The convenience of the balance controls is matched by the convenience with which various types of capacitors can be connected to the bridge for measurement. Two types of connector for the unknown capacitors are provided at the upper right corner of the bridge panel: a pair of TYPE 874 Coaxial Connectors and a set of three TYPE 938 Binding Posts with standard ¾-inch spacing. For three-terminal measurements with complete shielding, as is required particularly for very small capacitance, three-terminal capacitors, such as the TYPE 1403 Standard Air Capacitors and TYPE 1422-CD Precision Capacitor, can be connected with coaxial cables to the coaxial bridge terminals. Capacitors having other common types of coaxial connectors can also be connected to the bridge terminals by the use of the appropriate TYPE 874-Q Adaptor. Capacitors, such as the TYPE 1401 and TYPE 1409 Standard Capacitors, which have TYPE 274 Plugs as terminals, can be plugged into the jack-top binding posts. The binding posts can also be used for the connection of patch cords and leads of many types.

The appropriate set of unknown terminals is connected to the bridge (and the unused terminals disconnected) by means of a four-position terminal switch located next to these terminals. As this switch is moved to change terminals, it also shows the corresponding changes of connections and grounds in the simple circuit which is engraved on the panel. This simple circuit diagram does not replace the operating instruction manual, but it does serve even the constant user as a useful and ever-present reminder of the circuit which is in use and of the possible sources of measurement or connection error.

When the terminal switch is set in the position marked CAL, the L or detector side of all the terminals is disconnected. This permits a check or self-calibration of the bridge capacitors at any time without the need for disconnecting the unknown.

Three-Terminal

In the next position, marked 3 TERM, the coaxial TYPE 874 unknown terminals are connected to the bridge, with the L terminal connected to the detector and the H terminal to the transformer. The shields of the connectors and all ground points on the bridge are connected to the guard point, so that all capacitances to the shields or to ground are excluded from the direct capacitance between H and L measured by the bridge.

The third position of the switch, marked 3 TERMINAL, connects to the bridge the H, L, and GND binding posts instead of the coaxial terminals. The H post is connected to the transformer, the L post to the detector, and the GND post to the transformer midpoint and bridge ground. As in the coaxial three-terminal measurement, the bridge measures only the direct capacitance between the H and L posts and excludes capacitances from H or L to any GND or guard point. The open binding posts have a direct capacitance of about 0.2 pf, which must usually be measured and subtracted from the value measured when a capacitor is connected. The bridge can, of course, measure this small terminal capacitance, as well as that of any leads connected between terminals and capacitor.

Two-Terminal

The fourth position of the switch, marked 2 TERMINAL, deserves special attention because of the important changes it makes in bridge connections and bridge measurements. The bridge is again connected to the binding-post terminals with the H post connected to the transformer, but the L and GND posts are now connected together and to the bridge case and panel and to any external ground used. The bridge now measures *all* capacitances between the H terminal and L or GND, including stray capacitances from post and leads to the panel and other environment. These are the capacitances measured by the common two-terminal capacitance bridge, so that it is possible to duplicate with the new TYPE 1615-A Capacitance Bridge the measurements of two-terminal capacitors obtained with older bridges, such as the TYPE 716-C Capacitance Bridge.

In principle, this change of the inherently three-terminal transformer bridge to two-terminal operation is made as shown in Figure 4; the ground point is simply switched from the center of the transformer arms to the junction of the standard and unknown capacitors, thereby grounding one side of the unknown. In practice, this change is complicated by the fact that the center of the transformer, which is the guard point to which the bridge shields are connected, is then connected to the high-impedance side of the detector instead of to ground. To prevent error voltages from entering the detector, all the wires and bridge shields connected to the high side of the detector must be enclosed by a grounded shield. To provide this extra shielding for two-terminal measurements, the bridge components are enclosed in an inner shield box which is enclosed by but insulated from the outer box and panel, and the primary of the main ratio transformer is also enclosed in two separate shields.

External Standards

Range Extension

The usefulness of the bridge is further increased by the provision on the bridge panel of a pair of terminals to permit the connection of an external standard capacitor or resistor to supplement or replace the standards in the bridge. This pair of coaxial TYPE 874 Connectors, located to the left of the coaxial pair for the unknown, has the L terminal connected to the L terminal of the unknown and the H terminal connected to the standard side of the transformer through a rotary switch, by means of which any of the ten steps of voltage from the transformer can be applied to the external standard. This rotary switch, with its digital readout through a window, provides a seventh decade of capacitance or a fifth of conductance whose magnitude is determined by the external standard chosen. For example, the capacitance range can be extended to 11 μf by the connection of an external standard of 0.01 μf. With the C MAX range lever set at the 1 μf maximum, the rotary decade then provides a balance control of 1 μf per step and the lever switches extend the balance range six more decades from 0.1 μf through 1 pf per step.

Accuracy Extension

Since both the unknown and external standard capacitors can be connected to a wide range of accurate transformer ratios, a comparison of external capacitors can be made with an accuracy even higher than that of the direct bridge reading; and the ratios can be chosen so that the magnitudes of the external capacitors do not have to be decade multiples. For example, suppose a standard capacitor of 1000 pf is available with a calibration accuracy higher than 0.01%. This accuracy can be transferred to a capacitor of, say, 5000 pf by connecting that capacitor to the appropriate unknown terminals and the 1000-pf standard to the external standard terminals. When the rotary decade switch for the external standard is set to 0.5 and the C MAX lever to the 0.01-μf position (where M = 10), the external standard is effectively multiplied by 5 to balance the unknown. Small differences between the external capacitors can, of course, be balanced with the bridge capacitance and conductance decades, and any small errors in the bridge reading of the difference are insignificant in the comparison measurement as long as the difference is a small percentage of the total capacitance.

Resolution Extension

The resolution, as well as accuracy, of the bridge can be extended by the use of an external standard capacitor. It has already been noted above that the external standard and its decade switch add a seventh decade, which can have increments either larger or smaller than those of the six lever decades. Even higher resolution is possible when, for example, two 1000-pf external capacitors are compared, because the bridge decades can be used to measure a difference as small as 0.00001 pf or 1 part in 10^8 in this example. Usable resolution of 0.1 ppm is not hard to obtain with the recommended TYPE 1232-A Null Detector, but higher resolution usually requires special detectors.

GENERATOR AND DETECTOR

The fact that the instrument contains neither generator nor detector may not seem a convenience to the occasional user of the TYPE 1615-A Capacitance Bridge, but it is often an engineering and economic advantage. A generator and a detector in separate packages can be better selected or modified to fit the many uses of the bridge over its wide range of capacitance and frequency. For most of the uses and most of the range, the recommended generator is the new TYPE 1311-A Audio Oscillator[4] and the recommended detector is the TYPE 1232-A Tuned Amplifier and Null Detector.[5] A complete system for capacitance measurement, consisting of the bridge and the recommended generator and detector, is available as the TYPE 1620-A Capacitance-Measuring Assembly, illustrated on page 14.

— J. F. Hersh

CREDITS

The TYPE 1615-A Capacitance Bridge was developed by John F. Hersh. Others contributing to the final design are R. A. Soderman, Administrative Engineer; G. A. Clemow, Design Engineer; G. C. Oliver, Design Draftsman; W. H. Higginbotham, Production Engineer, and W. G. Cooper, Assistant Test Engineer.

— EDITOR

[4]Described elsewhere in this issue.

[5]A. E. Sanderson, "A Tuned Amplifier and Null Detector with One-Microvolt Sensitivity," *General Radio Experimenter*, 35, 7, July, 1961.

SPECIFICATIONS

Capacitance Range (6 ranges): 10^{-17} to 10^{-6} farads (10 μpf to 1μf), direct reading; 6-figure resolution, smallest division 10^{-17} farads.

Dissipation-Factor Range (3 ranges): 0.000001 to 1 at 1 kc, direct reading. Directly proportional to frequency at other frequencies. Four-figure resolution; smallest division, 0.000001.

Conductance Range (2 ranges +; 2 ranges −): 10^{-6} μmho to 100 μmho; 4-figure resolution, smallest division 10^{-6} μmho; independent of frequency; varies with C range.

Accuracy:

Capacitance—direct reading, internal standard, ±0.01%, except at the extremes of the range. At high capacitance and high frequency, error is $+ 0.002\% \, C_{\mu f} \left(\frac{f}{1000}\right)^2$. At low capacitance and low frequency, accuracy may be limited by bridge sensitivity.

Capacitance—comparison with external standard, approximately 1 ppm.

Dissipation factor, ±(0.1% + 10 ppm) of measured value.

Conductance, ±(1% + 0.00001 μmho).

Frequency Range: Approximately 100 cycles to 10 kc.

Temperature Coefficients of Internal Standards: Less than 5 ppm/°C for the 1000-, 100-, and 10-pf units; slightly greater for the smaller capacitance units.

Maximum Voltage: 20 volts at 1 kc. Proportional to frequency.

Accessories Required: Generator and detector; the Type 1311-A Audio Oscillator and the Type 1232-A Tuned Amplifier and Null Detector are recommended.

Accessories Supplied: Type 874-WO Open-Circuit Termination, Type 874-R22 Patch Cord, and Type 274-NL Patch Cord.

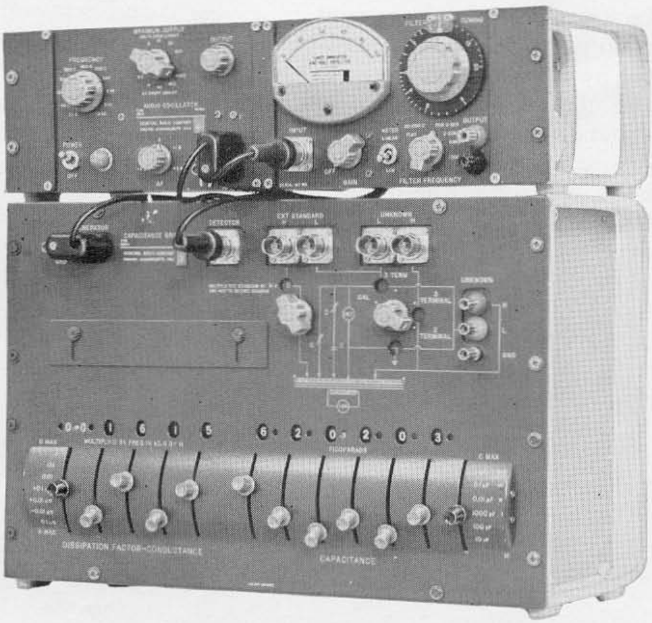
Dimensions: Width 19, height 10½, depth 12¾ inches (485 by 270 by 325 mm), over-all.

Net Weight: 38½ pounds (17.5 kg).

Type		*Code Word*	*Price*
1615-AM	**Capacitance Bridge, Bench Model........**	ATTIC	**$1475.00**
1615-AR	**Capacitance Bridge, Cabinet Model......**	BALMY	**1475.00**

U.S. Patent No. 2,548,457.

TYPE 1620-A CAPACITANCE-MEASURING ASSEMBLY



The Type 1620-A Capacitance-Measuring Assembly consists of the Type 1615-AM Capacitance Bridge with the Type 1311-A Audio Oscillator and the Type 1232-A Tuned Amplifier and Null Detector, thus providing a complete system for the precise measurement of capacitance over the range of 10 μpf to 1 μf (10^{-17} to 10^{-6} farads). Frequency range is approximately 50 cps to 10 kc. The system has sufficient sensitivity to realize the full six-place resolution of the bridge for all measurements except for very small capacitances at the lower frequencies.

Oscillator and detector are mounted side by side as shown in the photograph. The end frames are bolted together to make a rigid assembly without the use of a relay rack. Connection cables are supplied.

The oscillator operates from the power line, the detector from internal batteries.

Type		*Code Word*	*Price*
1620-A	**Capacitance-Measuring Assembly**................	ORBIT	**$2080.00**

HIGH PERFORMANCE, LOW-COST AUDIO OSCILLATOR WITH SOLID-STATE CIRCUITRY

Modern solid-state circuitry is used in the new TYPE 1311-A Audio Oscillator to produce a self-contained, compact, inexpensive instrument with many desirable features. Among these are high-power output into a wide range of load impedances, low-distortion even when the load impedance is short-circuited, excellent stability, low noise, and very small size.

The TYPE 1311-A Audio Oscillator supplies power at eleven commonly used

Figure 1. Panel View of the Type 1311-A Audio Oscillator.