THE General Radio EXPERIMENTER

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

VOLUME XXI No. 11 APRIL, 1947

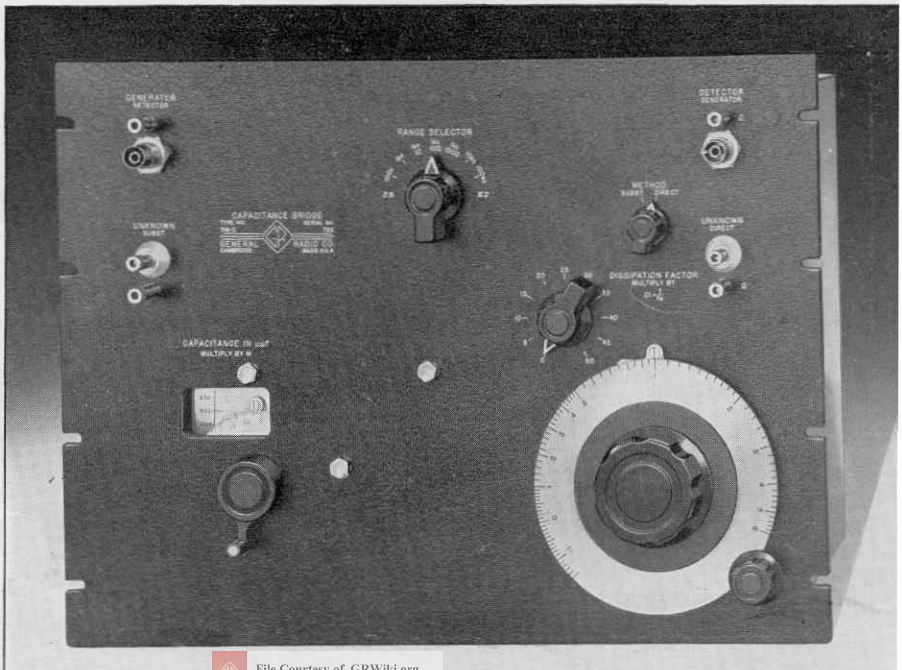
A WIDE-FREQUENCY-RANGE CAPACITANCE BRIDGE

Also

IN THIS ISSUE

● **THE CONSTANTLY** expanding spectrum of frequencies used by the radio engineer has stimulated the study of the dielectric properties of insulating materials and of the characteristics of capacitors over an ever-widening range of frequency. During the war measuring techniques were developed to keep pace with radar, pushing the upper frequency limit first to 3000 Mc with coaxial line apparatus and then to 10,000 Mc with wave-guide apparatus. The lower frequency limit of such equipment is about 200 Mc, which in turn is the upper limit of the susceptance-variation circuit. The Schering bridge and the susceptance variation circuit

Figure 1. Panel view of the Type 716-C Capacitance Bridge.



overlap, the latter extending down to 100 kc, and the former reaching at least to 10 Mc.

The Type 716-B Capacitance Bridge used the Schering bridge circuit, but has been limited to audio-frequencies within a factor of 3 below or above 1 kc. During the last four years some 25 of these bridges have been converted to Type 716-BS2 Capacitance Bridges to operate from 30 c to 300 kc for capacitance measurements up to 1000 $\mu\mu$f, while maintaining a capacitance range up to 1 μf at 1 kc. The new Type 716-C Capacitance Bridge, which supersedes the Type 716-B, incorporates these changes. A panel view of the new bridge is shown in Figure 1.

CIRCUIT

The circuit is that of the well-known Schering bridge, the arrangement of which is shown in Figure 2. The simplified conditions of balance are given by:

$$C_X = C_N \frac{R_A}{R_B}$$

$$D_X = R_X \omega C_X = R_A \omega C_A = Q_A$$

At any given frequency and value of R_A, the capacitor C_A can be calibrated to be direct reading in dissipation factor. The standard capacitor can be calibrated directly in micromicrofarads, and the capacitance range extended by switching the resistance R_B in decade steps. In the Type 716-C Capacitance Bridge, the capacitance C_A consists of an air capacitor and a mica decade capacitor, connected in parallel by suitable switching.

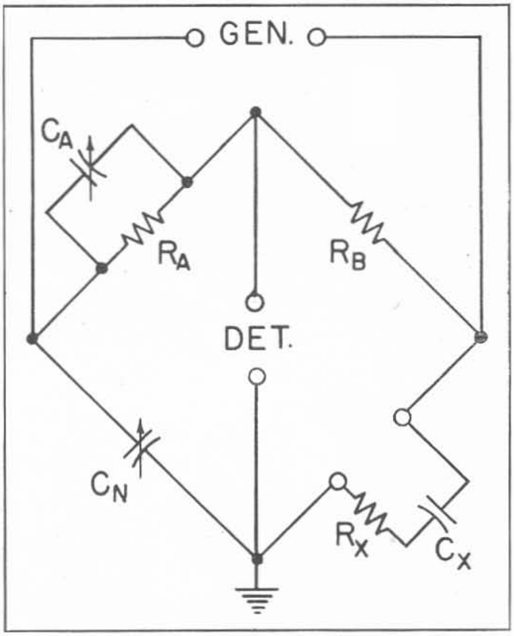


Figure 2. Elementary circuit of the Schering Bridge.

The air capacitor has a maximum capacitance of approximately 500 $\mu\mu$f. Connected across 20,000 ohms, this gives a maximum dissipation factor range of about 0.06 at 1000 cycles. The mica decade provides ten additional steps of 0.05 each, thus making a total range of 0.56.

The standard capacitor C_N is calibrated directly in $\mu\mu$f from about 100 $\mu\mu$f to 1100 $\mu\mu$f, and the total capacitance range of the bridge is extended to .011, .11, and 1.1 μf by changing the resistor R_B to 2000, 200, and 20 ohms, respectively. In order to maintain the feature of direct-reading dissipation factor, a suitable capacitor is connected in parallel with each value of R_B, to make the product $R_B C_B$ of the arm equal to the product $R_A C_{AO}$ of the arm A.

For substitution measurements of capacitance of 1000 $\mu\mu$f or less, the bridge is first balanced with a capacitor C_P connected in the P arm, whose capacitance is at least 100 $\mu\mu$f greater than that of the unknown capacitor. A second balance is obtained with the unknown capacitor connected in parallel with the standard capacitor C_N.

$$C_X = C' - C = \Delta C$$

$$D_X = \frac{C'}{C' - C}\left(R_A \omega C_A - R_A \omega C'_A\right)$$

$$= \frac{C'}{\Delta C} \Delta Q_A$$

In order that the dissipation factor dial shall read up scale when the unknown capacitor is connected across the N arm, a method switch is provided, which in its substitution position, as shown in Figure 3, transfers the dissipation factor capacitors C_A to the B arm and places across the A arm a capacitance equal to twice the zero capacitance C_{AO} of the A arm.

EXTENSION OF FREQUENCY RANGE

Superficially, the problem of obtaining direct-reading scales at several different frequencies is merely that of switching the ratio-arm resistors. Although the equation of balance for capacitance is independent of frequency, that for dissipation factor is dependent on frequency in such a manner that, for a given R_AC_A combination, the range of dissipation factor is directly proportional to frequency. In order to retain the same range as the frequency is changed, it is necessary to change either R_A or C_A in inverse proportion. For several reasons, not the least of which is the obvious economic one, the change is accomplished by switching to a new value of R_A and its associated compensating capacitor. Simultaneously, of course, R_B must be switched, in order to retain the capacitance range.

The problem of satisfactory wide-frequency-range operation involves more than ratio-arm switching, however. Among the difficulties encountered are those due to

(*a*) Inductance of circuit elements and wiring.

(*b*) Leakage between primary of coupling transformer and bridge circuit.

(*c*) Insufficient transformer response at extremes of frequency range.

It is largely the limitations of (*a*) that have determined 100 kc as the highest nominal frequency for the bridge. The errors introduced by inductance vary, in general, as the square of the frequency; and, while negligible at 100 kc and with 200-ohm ratio arms, become intolerable at 1 megacycle and with 20-ohm ratio arms. These errors could be reduced to a tolerable value only by a drastic mechanical redesign of the bridge and its components, an objective not contemplated at the present time.

THE COUPLING TRANSFORMER

The principal design problem has been associated with the transformer used to couple the generator voltage to the bridge circuit. Ideally this transformer should introduce across the bridge circuit only that voltage magnetically induced in its secondary.

Actually, any transformer will have, in addition to this desired inductive coupling, capacitive and conductive

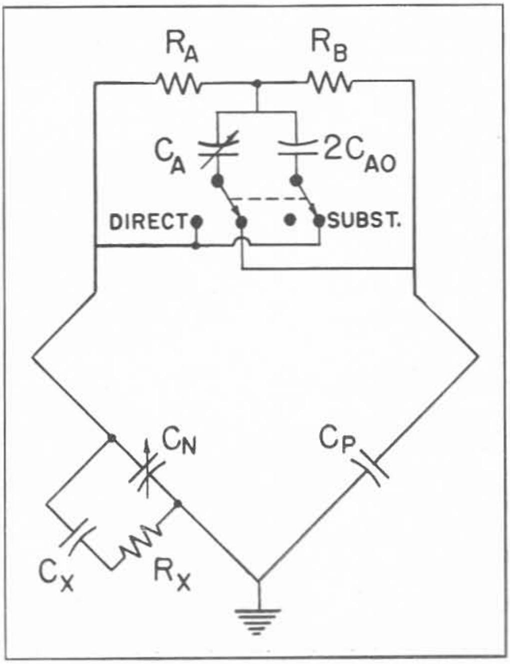


Figure 3. Method of switching from direct to substitution measurements.

File Courtesy of GRWiki.org

couplings between the primary winding and the secondary winding and shields. Any high-impedance bridge circuit is extremely sensitive to the effects of these extraneous couplings. In the design of the transformer for this bridge, unusual precautions have been taken to shield the primary winding. The input is by way of a coaxial lead brought directly into the winding with its shield soldered to the winding shield. The latter completely encloses the primary winding except for the necessary slot, which is overlapped. Similar precautions are taken with the other shields; but nevertheless, a total residual coupling capacitance of the order of a few hundredths $\mu\mu$f remains, due probably to leakage through the braid of the concentric cable and fringing through the slots of the shields.

The dissipation factor of this coupling capacitance, which would supply a conductive coupling, has been reduced to a negligible value by the use of polystyrene tape for the insulation between shields. In all of the transformers used in the previous models, paper and hard rubber insulation was used and the resulting conductive coupling was sufficient to cause an error approaching 0.0005 in dissipation factor for small capacitance settings.

The effect of this coupling capacitance depends on the phase of the primary voltage across the bridge and at high frequencies is such as to produce significant errors in dissipation factor readings. To counteract this effect, a second voltage opposite in phase to the primary voltage is coupled to the bridge through a small capacitance. By proper adjustment of this coupling capacitance, the effect of the undesirable coupling is "neutralized." The problem is very similar to that encountered in the triode amplifier where grid-plate capacitance causes undesirable coupling between grid and plate circuits. The solution also is similar, as the method employed here bears a strong resemblance to the "neutralization" methods commonly employed in radio-frequency power amplifiers. The out-of-phase component of voltage is conveniently taken from the half-turn potential of the primary shield, the mid-point of which is grounded.

Maximum useful frequency range of the transformer is achieved by the use of high-permeability core material, with a one-to-one turns ratio. For the normal connection of the bridge, the one-to-one ratio means a sacrifice in sensitivity of about three to one as compared to the 716-B with its four-to-one winding ratio. On the other hand, a three-to-one *gain* in sensitivity over the 716-B is realized when the generator and detector connections are interchanged. This latter connection is frequently used at 60 cycles as it permits voltages up to 700 volts to be impressed on the unknown

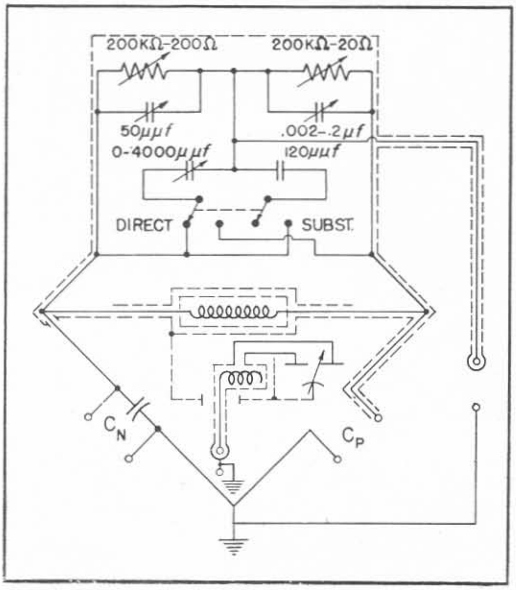


Figure 4. Schematic circuit diagram of the Type 716-C Capacitance Bridge, showing arrangement of transformer shields.

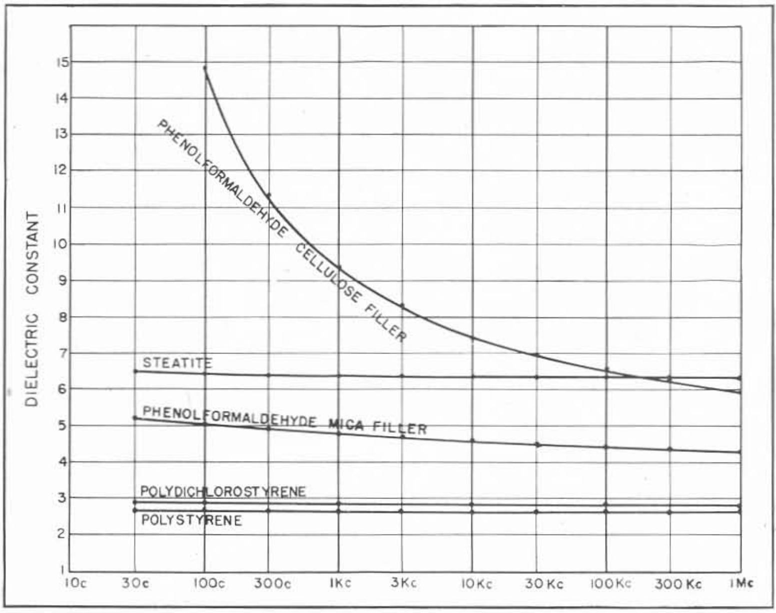
capacitance, compared to 50 volts for the normal connections. When the bridge is so connected, the transformer is operated, at balance, at zero signal level and must be protected against magnetic pickup. Such protection is provided by a case of high-permeability material which reduces pickup by more than 40 db.

The complete schematic diagram of this bridge is given in Figure 4. The transformer capacitance is placed across the *B* arm instead of the *A* arm in order to keep the zero capacitance of the ratio arms as small as possible.

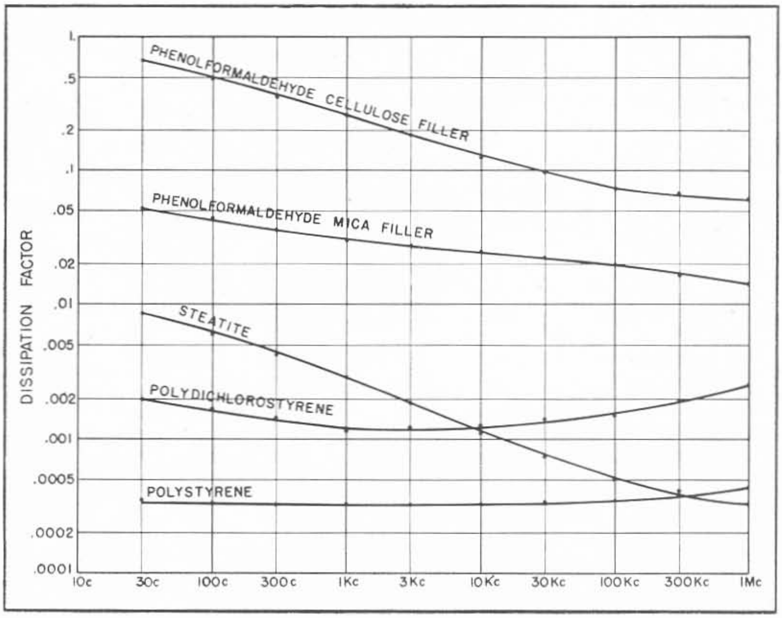
ACCURACY

The same accuracy for both capaci-

Figure 5. Typical measurements with the Type 716-C Capacitance Bridge.



(*Left*) Variation of dielectric constant with frequency for several dielectric materials.



(*Right*) Variation of dissipation factor with frequency as measured on the bridge.

tance and dissipation factor that obtained in previous models of the bridge at 1 kc, and which is stated in the specifications below, holds in the 716-C from 30 c to 300 kc, provided the bridge is always operated within a factor of 3 of its direct-reading range frequency. Substitution measurements can be made to the same accuracy up to 1 Mc provided the unknown capacitance is less than 500 μμf.

USES

Aside from the normal uses of the bridge in measuring any capacitor within its range for both capacitance and dissipation factor, there are many other uses for which its accuracy and wide capacitance and frequency ranges particularly adapt it. Perhaps its most important use is in the intercomparison of sets of standards, such as Type 509 Condensers. This intercomparison can be made to an accuracy of 0.02% for capacitance and 0.00005 for dissipation factor. Absolute values of capacitance have an accuracy of only 0.2% except where one or more of the standards have been certified by the National Bureau of Standards. The capacitance range of such intercomparisons can be extended with some loss in accuracy down to 1 μμf using special Type 722 Precision Condensers and up to 1 mf (1000 μf) using suitable groups of oil-filled paper capacitors.

Another important use of the bridge is in measuring the dielectric constant and dissipation factor of dielectric samples over the frequency range from 30 c to 1 Mc. Contained within this range are the effects of interfacial polarization at low audio-frequencies and of dipole polarization in polymers. The effect of surface water films can also be studied.

This bridge offers one of the best methods of measuring the Boella effect in high valued resistors. This effect results from the distributed capacitance occurring in such resistors. The value of this distributed capacitance and any parallel lumped capacitance is also determined. Whenever in a lower-valued resistor the effect of its series inductance outweighs that of its parallel capacitance, the value of this series inductance can be determined. In the same manner, the frequency characteristics of a large inductor or choke coil can be determined as it passes through its natural frequency and becomes capacitive.

R. F. Field
I. G. Easton

SPECIFICATIONS

Ranges: Direct Reading—capacitance, 100 μμf to 1 μf at 1 kc; 100 μμf to 1100 μμf at 100 c, 10 kc, and 100 kc; dissipation factor, 0.00002 to 0.56.

Substitution Method—capacitance, 0.1 μμf to 1000 μμf with internal standard; to 1 μf with external standards; dissipation factor, $0.56 \times \frac{C'}{C_x}$ where C' is the capacitance of the standard condenser and C_x that of the unknown.

Accuracy: Direct Reading — capacitance, ±0.2% or ±2 μμf × multiplier reading (0.2% of full scale for each range) when the dissipation factor of the unknown is less than 0.01; dissipation factor ±0.0005 or ±2% of dial reading, for values of D below 0.1.

Substitution Method—capacitance ±0.2% or ±2 μμf; dissipation factor, ±0.00005 or ±2% for change in dissipation factor observed, when the change is less than 0.06.

A correction chart for the precision condenser is supplied, giving scale corrections to 0.1 μμf at multiples of 100 μμf. By using these data, substitution measurements can be made to ±0.5 μμf.

When the dissipation factor of the unknown exceeds the limits given above, additional errors occur in both capacitance and dissipation-factor readings. Corrections are supplied, by means of which the accuracy given above can be maintained over the entire range of the bridge.

Ratio Arms: The arm across which the dissipation factor condenser is normally connected at 1 kc has a resistance of 20,000 ohms. The other arm has four values, 20,000 ohms, 2000 ohms, 200 ohms, 20 ohms, providing the four multiplying factors 1, 10, 100, 1000. Suitable condensers are placed across these arms so that the product RC is constant. At 100 c, 10 kc, and 100 kc the ratio arms are equal and have resistances of 200,000 ohms, 2000 ohms, and 200 ohms, respectively.

A switch is provided for shifting the dissipation-factor condensers to the other ratio arm when the substitution method of measurement is used, so that the dissipation-factor dial will read up-scale.

Standards: Capacitance, Type 722 Precision Condenser direct reading from 100 $\mu\mu$f to 1100 $\mu\mu$f; dissipation factor, Type 539-T Condenser with semi-logarithmic scale and decade-step condenser calibrated directly in dissipation factor.

Shielding: Ratio arms, dissipation-factor condensers, and shielded transformer are enclosed in an insulated shield. The unknown terminals are shielded so that the zero capacitance across them is not greater than 1 $\mu\mu$f. A metal dust cover and the aluminum panel form a complete external shield.

Frequency Range: All calibration adjustments are made at 1 kc and the accuracy statements above hold for operating frequencies from 30 c to 300 kc, provided the operating frequency does not differ from the range selector frequency by more than a factor of three. Dissipation-factor readings must be corrected by multiplying the dial reading by the ratio of operating frequency to the range selector frequency.

Voltage: Voltage applied at the GENERATOR terminals is fed to the bridge through a 1-to-1 shielded transformer. A maximum of 1 watt can be applied, allowing a maximum of 300 volts at 1 kc, but only 50 volts at 60 c.

Power can also be applied at the DETECTOR terminals, and the detector connected to the GENERATOR terminals.

Mounting: The bridge is supplied for mounting on a 19-inch relay rack or for cabinet mounting.

Accessories Required: Oscillator and amplifier. For audio frequencies Type 1301-A Oscillator and Type 913-B Beat-Frequency Oscillator are satisfactory power sources. Type 1231-A Amplifier and Null Detector is recommended for use as the detector. For aural null indications, Western Electric 1002-C Telephones can be used with the amplifier. The Type 707-A Cathode-Ray Null Detector can also be used as a detector for frequencies up to 2 kc.

For substitution measurements, a balancing condenser is needed. This may be either an air-dielectric model, Type 539-B, or a fixed mica condenser of the Type 505 series.

Accessories Supplied: Two Type 274-NE Shielded Connectors.

Dimensions: (Length) 19 x (height) 14 x (depth) 9 inches, over-all.

Net Weight: 41½ pounds, relay-rack model; 53¾ pounds, cabinet model.

Type		*Code Word*	*Price*
716-CR	**For Relay-Rack Mounting**	BONUS	**$410.00**
716-CM	**Cabinet Mounted**	BOSOM	**450.00**

Add 10% to above prices.

MISCELLANY

Among the recent visitors to our plant and laboratories were four from Stockholm, Sweden: Mr. Carl A. Trapp, Chief Engineer of A. B. Riffa; Mr. Tord Wikland of the Research Institute for National Defense; Mr. Gunnar Svala, Chief Research Engineer, A. B. Svenska Electronrör, and Mr. Carl H. Sivers of L. M. Ericcson, Tu.

The Type 716-C Capacitance Bridge was developed by Robert F. Field and Ivan G. Easton, the authors of the article appearing in this issue. Mr. Field is a widely known authority on impedance measurements and the properties of dielectric materials, and has contributed a number of papers on these subjects to the journals of professional societies and to the *Experimenter*. Mr. Easton, who has been intimately associated with bridge development, will also be recognized as a frequent contributor to the *Experimenter*. He is at present in charge of our New York Engineering Office.

The Type 413 Beat-Frequency Oscillator, which, we believe, was the first instrument of its kind to be made