THE General Radio EXPERIMENTER

VOLUME XIX No. 4 SEPTEMBER, 1944

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

A METHOD FOR MEASURING SMALL DIRECT CAPACITANCES

Also IN THIS ISSUE

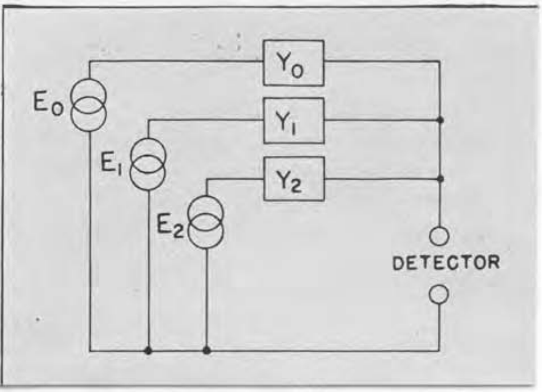
● **A PROBLEM** recently encountered in connection with the design of a shielded bridge transformer was that of measuring direct capacitances of the order of 0.01 $\mu\mu$f. The measurement could not be made on available bridges because of the small magnitude of the capacitances and the relatively large terminal admittances associated with them. A parallel-null method, using the TYPE 546 Microvolter and the TYPE 736-A Wave Analyzer, was found satisfactory and is described below.

Theory of the Method

The method is basically a parallel-transmission null method such as is used in the TYPE 561-D Vacuum-Tube Bridge. It resembles both bridge and parallel-T methods, but differs from both in several important respects. It also resembles the so-called "charging-current" methods commonly used for the measurement of interelectrode capacitances, but differs fundamentally from such methods in that it utilizes a null balance rather than a calibrated deflection to determine the unknown admittance.

In Figure 1 are shown three voltages feeding through three separate admittances

FIGURE 1. Basic diagram of the parallel-transmission null method. The relation between the voltages and admittances for zero voltage across the DETECTOR terminals is given in the text.



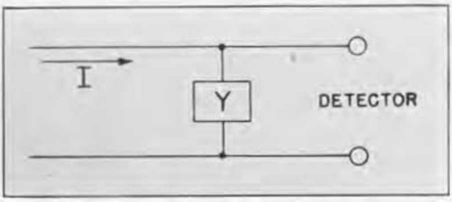


FIGURE 2. The circuit of Figure 1 can, by the application of Thevenin's Theorem, be reduced to the simple system shown.

to a common null detector.

The condition of balance can be derived most easily by reducing the system, as seen at the detector terminals, to a constant current generator shunted by its own internal admittance. The equivalent system is shown in Figure 2.

The total current I is simply the sum of the short-circuit currents produced at the detector by the individual voltages, i.e.:

$$I = E_0Y_0 + E_1Y_1 + E_2Y_2 = \sum E_nY_n \qquad (1)$$

The shunt admittance Y is the admittance at the detector terminals with the voltage sources short-circuited.

$$Y = Y_0 + Y_1 + Y_2 = \sum Y_n \qquad (2)$$

If the current $\sum E_nY_n$ is zero, the voltage across the detector terminals will be zero. Thus the condition of balance is

$$\sum E_nY_n = E_0Y_0 + E_1Y_1 + E_2Y_2 = 0 \qquad (3)$$

If the voltages E_1 and E_2 are 180° out of phase with E_0, we have

$$Y_0 = \frac{E_1}{E_0}Y_1 + \frac{E_2}{E_0}Y_2 \qquad (4)$$

Thus if Y_0 is an admittance $G_x + jB_x$ it can be balanced by adjusting E_1 in series with a susceptance B_1 and E_2 in series with the conductance G_2. For example, consider the circuit of Figure 3.

The equations of balance for the circuit shown are:

$$C_x = \frac{E_1}{E_0}C_1$$
$$G_x = \frac{E_2}{E_0}G_2 \qquad (5)$$

Inspection of the circuit and the equations of balance reveals several important features:

(*a*) Direct admittance is measured, as admittances to ground of the terminals of the unknown are thrown across the generator and detector, where they have no effect on the balance. Likewise, admittance to ground of the leads to the unknown does not affect the measurement.

(*b*) The two balance conditions are completely independent.

(*c*) The voltages E_1 and E_2 can be varied, by means of attenuators or voltage dividers, from *zero* to maximum value. This gives the equivalent of capacitors and resistors variable continuously over extremely wide ranges.

(*d*) Pure resistance or pure capacitance can be measured equally well by setting E_1 or E_2 to zero as required.

The equations of balance given above are of course derived for idealized conditions which can only be approximated in practice. The factors which have been neglected are:

(*a*) The dissipation factor of the "standard" capacitor.

(*b*) The shunt capacitance of the conductance G_2.

(*c*) Phase shift between the voltage E_0 and the voltages E_1 and E_2 (at audio frequencies caused largely by the leakage reactance of the transformer).

(*d*) The internal output impedance of the attenuators supplying E_1 and E_2.

The effect of these factors is mostly to introduce errors into the measurement of small quadrature components of admittance. For example, entirely erroneous results may be obtained in attempting to measure the *conductance* of a good capacitor, if these factors are not taken into account.

Sensitivity of Balance

The practical usefulness of any null balance method of measurement depends to a large extent on the sensitivity required of the detector, that is, on the magnitude of the change in output voltage for a given unbalance of the measuring circuit. The sensitivity of the system described can be analyzed as follows:

The *open-circuit* voltage appearing across the detector terminals of Figure 2 is given by

$$e' = \frac{I}{Y} = \frac{\sum E_n Y_n}{\sum Y_n} \qquad (6)$$

The *change* in open circuit output voltage for a small change in the admittances Y_0 is obtained by differentiation of (6) and can be written as

$$\Delta e' = \frac{E_0 \sum Y_n - \sum E_n Y_n}{(\sum Y_n)^2} \Delta Y_0$$

$$= \frac{\Delta Y_0}{\sum Y_n} \left\{ E_0 - \frac{\sum E_n Y_n}{\sum Y_n} \right\} \qquad (7)$$

But at balance $\sum E_n Y_n = 0$ and Equation 7 reduces to

$$\Delta e' = E_0 \frac{\Delta Y_0}{\sum Y_n} \qquad (8)$$

The actual voltage appearing across a detector having an admittance Y_d becomes

$$\Delta e = E_0 \frac{\Delta Y_0}{\sum Y_n + Y_d} \qquad (9)$$

In a circuit arranged for the measurement of small admittances, the circuit admittance $\sum Y_n$ will normally be small compared to the detector admittance Y_d under which circumstance Equation 9 reduces to

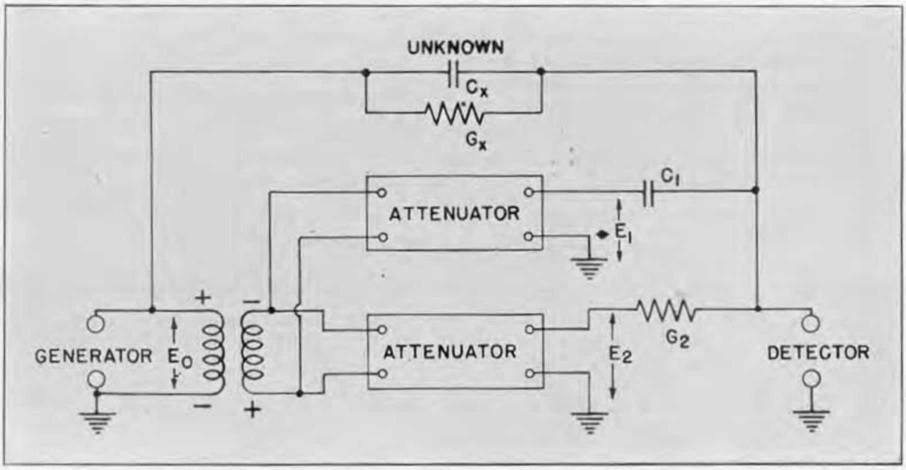
$$\Delta e = E_0 \Delta Y_0 Z_d \qquad (10)$$

Equation 10 states that the output voltage for a circuit unbalance ΔY_0 is simply the voltage developed across the detector by the unbalance current.

With particular reference to Figure 3 the minimum capacitance ΔC_x which can be *detected* will be

$$\Delta C_x = \frac{\Delta e}{E_0 \times \omega \times Z_d} \qquad (11)$$

FIGURE 3. Showing a practical circuit for the measurement of capacitance and conductance. As indicated, the transformer is connected to produce the phase reversal required for balance.



where E_0 is the applied voltage, Z_d the input impedance of the detector, and Δe the minimum detectable output voltage. Using the TYPE 736-A Wave Analyzer, which has an input impedance of 1 megohm and can easily detect 10 microvolts we have, using an input of 10 volts at 16 kilocycles,

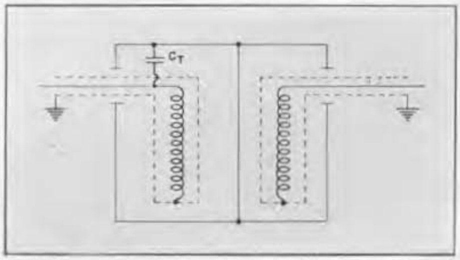
$$\Delta C_x = \frac{10\times10^{-6}}{10\times6.28\times16\times10^{3}\times10^{6}} \text{ farads}$$
$$= 10^{-5}\ \mu\mu\text{f}$$

Even allowing for considerable reduction of the detector input impedance by the shunt capacitance of circuit and leads, there is evidently adequate sensitivity for the measurement of very minute capacitance.

Detector Selectivity

As with any null balance method, selectivity in the detector is necessary in order to obtain the most satisfactory results. In the absence of selectivity the true balance may be masked by power-supply hum and amplifier noise. Also, the presence of harmonics in the signal source may obscure the fundamental balance or produce a false balance, if the conditions for balance depend upon frequency. For the circuit described, frequency does not explicitly enter the equations of balance, but, as a practical matter, either or both components of a complex admittance will vary with frequency, and the balance for the fundamental will not coincide with the balance for the harmonics.

FIGURE 4. Schematic diagram of doubly-shielded transformer. As this transformer is used, the outer shield is connected to the junction of the ratio arms of a Schering bridge. The capacitance C_T produces an error in dissipation factor reading under certain conditions.



EXAMPLES OF MEASUREMENTS

Transformer Capacitance

In Figure 4 is shown a schematic diagram of the shielded transformer mentioned earlier. Each winding is carefully shielded, with one side of each winding connected to its shield. In addition, there is a third shield, between the two winding shields, connected to the metal case which serves as a complete outer shield. The capacitance of particular interest is that between the primary lead and the center shield, as indicated in the sketch. In Figure 5 is drawn the reduced circuit showing this capacitance and its associated terminal impedances.

The measurement was made using a TYPE 546-A Microvolter[1] to adjust the current through the standard capacitor. A sufficiently sharp balance could be obtained in this case without providing a quadrature balance. It was found necessary to surround the transformer with a grounded shield and to use shielded connections in order to reduce the direct capacitance of the measuring circuit to a value small compared to that being measured.[2]

The standard capacitance used was a 100 $\mu\mu$f capacitor of the "postage stamp" variety. With the TYPE 546-A Microvolter, an input of 7.4 volts was required to produce an output of one volt. Accordingly, the unknown capacitance from Equation 5 is given by

---

[1] This model has a transformer built in. With the current model, TYPE 546-B, an external transformer must be used to obtain the phase reversal.

[2] If desired, an additional out-of-phase current path can be provided, to cancel out the effect of the initial capacitance.

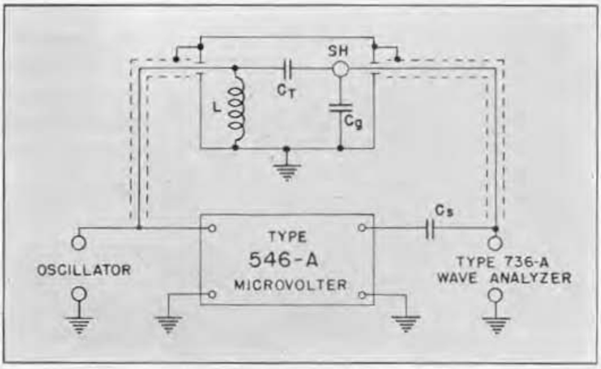


FIGURE 5. The circuit of Figure 4 reduced to show the capacitance C_T and its terminal impedances. The point marked *SH* represents the outer shield of the transformer. The capacitance C_g is the capacitance of this shield to ground, while *L* represents the inductance of the primary winding of the transformer. The entire transformer is enclosed in a grounded shield.

Shown also are the connections of the measuring circuit.

$$C_x = E\frac{C_S}{7.4}$$

where *E* is the reading of the microvolter dial at balance, in volts. By proper choice of the value of C_S or by adjusting the voltage applied to the microvolter (with a resistive voltage divider), the dial can be made direct reading in $\mu\mu$f.

No independent checks of accuracy were available for very small capacitances, but at 5 $\mu\mu$f (as measured against a TYPE 722-D Precision Condenser) the correct answer was obtained within the limit of accuracy of the calibration of the microvolter dial. Also, the capacitance between primary shield and secondary shield (of the order of 1 $\mu\mu$f) was measured by the method described. An independent determination with the transformer installed in the bridge checked within 0.01 $\mu\mu$f.

Interelectrode Capacitance

The type of measurement described obviously bears considerable similarity to the measurement of the interelectrode capacitance of vacuum tubes. A few measurements on representative tubes indicate that satisfactory results can be obtained in most cases. With properly designed, shielded sockets,[3] this method should give accurate results for the plate-grid capacitance of screen-grid tubes.

—IVAN G. EASTON

---

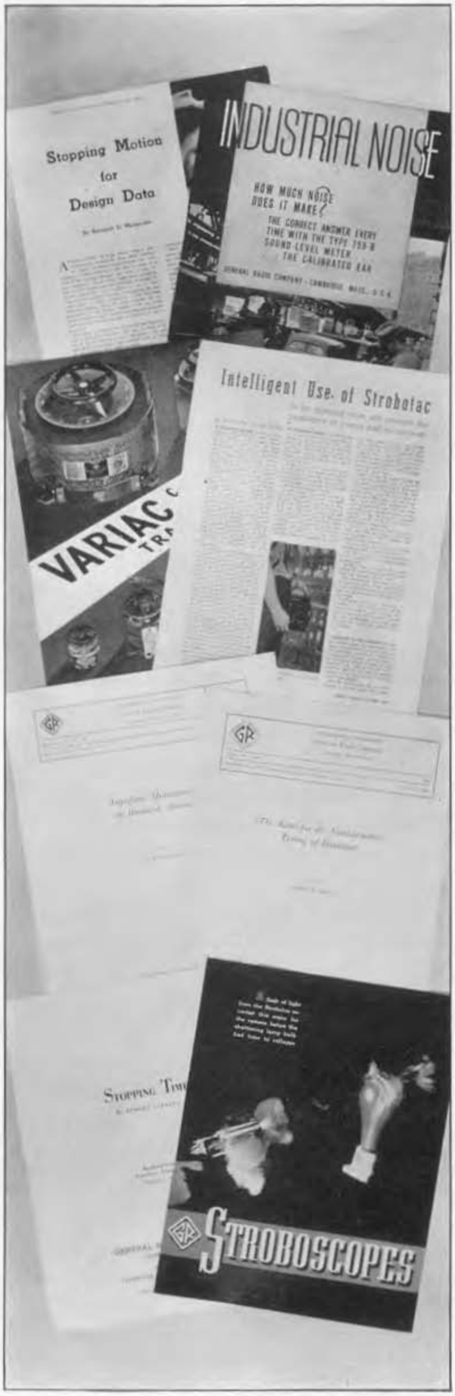
[3] See, for instance, "The Dependence of Interelectrode Capacitance on Shielding"—Leonard T. Pockman, *Proc. I.R.E.*, Vol. 32, No. 2, February, 1944, pps. 91–98.

TECHNICAL AND PRODUCT LITERATURE

● **WE HAVE A NUMBER** of publications available that engineers may find useful. These include bulletins describing General Radio products, their applications, and technical literature and charts.

Eyes for Industry—A handbook of stroboscopic techniques. This booklet outlines the principles on which General Radio stroboscopes operate and describes typical uses. Qualitative and quantitative measurements are discussed, as well as high-speed, single-flash photography.

Stroboscopes—A folder describing the Strobotac and Strobolux and illustrating typical uses. Ask for Form 420-D.



Stopping Motion for Design Data—by Kenneth D. Moslander. Reprint of an article on the use of the stroboscope by design engineers. This article was originally published in MACHINE DESIGN for June, 1941.

Intelligent Use of the Strobotac—by Raymond W. Mitchem. Reprint of an article from the October, 1942, issue of TEXTILE WORLD. This article discusses the practical application of the Strobotac in the spinning room and shows how it helps increase production without increasing the cost of the finished yarn.

Stopping Time—by Robert Littell. Reprint of an article on stroboscopes from the February, 1940, issue of THE SCIENTIFIC AMERICAN. This article was subsequently published in READERS' DIGEST.

The Noise Primer—The ABC of noise and vibration measurements. Discusses the characteristics of noise and vibration and the principles underlying their measurement. General Radio instruments for measuring and analyzing noise and vibration are described and details of their use are given.

Industrial Noise—A folder describing the General Radio TYPE 759-B Sound-Level Meter and its use in Noise Measurement.

Variacs—Folder describing the complete line of General Radio Variac autotransformers.

Heat Control Units—by John A. Riddick. Reprinted from INDUSTRIAL AND ENGINEERING CHEMISTRY, Analytical Edition, April 15, 1940. Describes a heat control system, using Variacs, on a fractionating column in the chemical engineering laboratory.

Impedance Bridges Assembled from Laboratory Parts—Reprint of a series of articles from the Experimenter. Discusses how audio-frequency impedance bridges can be assembled in the laboratory. Circuits and sources of error are covered, and examples of measurements are given.

Insulation Testing at Low Voltage—Booklet describing the use of the Type 740-BG Capacitance Test Bridge in power factor tests on bushings and insulators.

Portable Stage Lighting Control—by R. B. Lewis and L. T. Herndon, Jr. Reprint of an article from the Experimenter, describing the portable stage lighting equipment, with Variac control, built at the Glendale, California, Junior College.

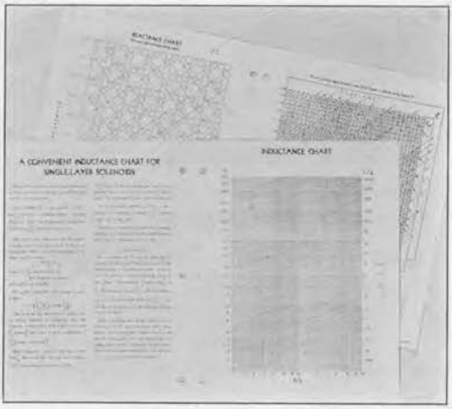
A Simple and Precise Standard of Musical Pitch—by Horatio W. Lamson. Reprint of an article in the July, 1935, issue of The Journal of the Acoustical Society of America. Describes the use of a 440- cycle electrically-driven tuning fork as a standard of musical pitch.

The Basis for the Non-Destructive Testing of Insulation—by R. F. Field. Reprint of a paper from Transactions of the A. I. E. E. for September, 1941. An analysis of the physical nature of dielectrics, the mechanism of deterioration and breakdown, with an outline of non-destructive methods of measurement.

Impedance Measurements on Broadcast Antennas—by D. B. Sinclair. Reprinted from Communications, June and July, 1939. A summary of methods of measuring antennas and lines at broadcast frequencies, with a discussion of sources of error.

Reactance Chart—A wide-range, easy-to-use chart relating reactance, capacitance, inductance, and resonant frequency. Available in $8\frac{1}{2}''$ x $11''$ size, punched for a three-ring binder and also in larger size for wall mounting.

Inductance Chart—A handy chart for determining the number of turns and the size of wire necessary to obtain a given inductance on a given winding form. Available in two sizes, for notebook and wall mounting.



SINCLAIR APPOINTED ASSISTANT CHIEF ENGINEER

Dr. Donald B. Sinclair of the General Radio engineering staff has been appointed Assistant Chief Engineer and will be in charge of circuit development.

Dr. Sinclair was born in Winnipeg, Manitoba, in 1910. He attended the University of Manitoba from 1926 to 1929. He received the degree of S.B. from the Massachusetts Institute of Technology in 1931, S.M. in 1932, and Sc.D. in 1935. Prior to joining the General Radio engineering staff in 1936, he was a Research Assistant at M.I.T. from 1932 to 1935, and a Research Associate in 1935 and 1936. Dr. Sinclair is a member of Sigma Xi and a Fellow of the Institute of Radio Engineers.

GENERAL RADIO COMPANY
275 MASS. AVE. - CAMBRIDGE 39, MASSACHUSETTS
BRANCH ENGINEERING OFFICES
90 WEST STREET, NEW YORK CITY 6
920 SOUTH MICHIGAN AVENUE, CHICAGO 5, ILLINOIS
1000 NORTH SEWARD STREET, LOS ANGELES 38, CALIFORNIA