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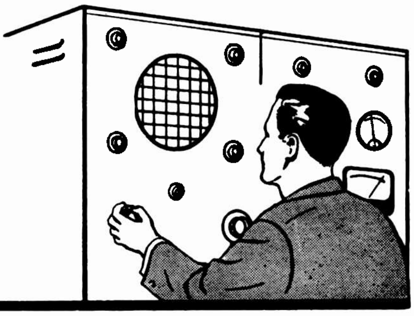

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Substitution-Type Capacitance-Measuring Circuits

By the Engineering Department, Aerovox Corporation

Capacitance measurement by the substitution method offers several advantages: it is (1) unaffected by stray circuit capacitances, (2) is relatively simple, (3) is adaptable to audio and radio frequencies, (4) is especially useful for measuring small capacitances, and (5) requires only the simplest calculation — subtraction.

A substitution circuit may be assembled quickly from laboratory equipment, or a substitution-type capacitance meter may be built as a permanent instrument. While the principle of substitution capacitance measurement is not new, and commercial instrumentation is available, we feel that components and circuitry introduced since we last discussed the subject ("Practical Methods of Testing Condensers," Part 3, *Aerovox Research Worker,* March 1938) warrant a fresh survey of the art.

BASIC METHOD

The heart of the substitution circuit is a calibrated variable capacitor. This usually is a variable air capacitor with a dial reading direct in micromicrofarads, but it can be a capacitor decade when higher capacitances are needed than can be supplied by an air capacitor. This capacitor is connected in a circuit (such as a bridge or LC tank) which may be tuned or balanced at the maximum capacitance setting of the capacitor. Terminals for connection of the unknown capacitance are arranged in parallel with the variable capacitor.

Figure 1 shows three basic substitution circuits. In each of these, X-X are the terminals for the unknown capacitor.

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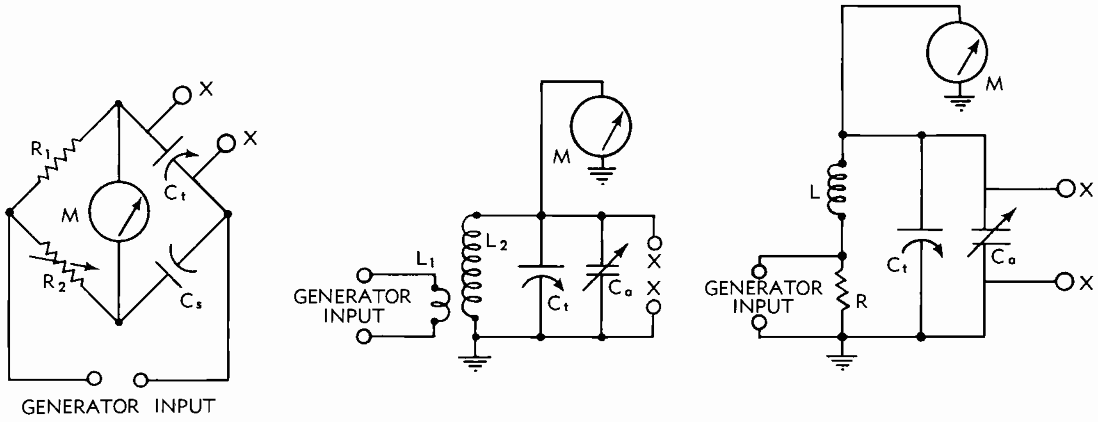


(A) BRIDGE

(B) RESONANT CIRCUIT INDUCTIVELY COUPLED

(C) RESONANT CIRCUIT RESISTANCE COUPLED

BASIC SUBSTITUTION-TYPE CIRCUITS

Figure 1

Figure 1 (A) is a convention 4-arm bridge. Here, the variable capacitor (C_t) is one arm of the bridge. This scheme often is used with a convenient capacitance bridge by connecting a dial-calibrated variable capacitor solidly to the unknown terminals which also serve as terminals X-X. The bridge first is balanced (by adjustment of R_2) with C_t set to maximum capacitance (C_1). The setting of R_2 is not subsequently disturbed. Next, the unknown capacitor is connected to terminals X-X. This added capacitance upsets the bridge. Finally, the setting of C_t is reduced to a capacitance (C_2) at which the bridge is rebalanced. The unknown capacitance then is calculated: $C_x = C_1 - C_2$. Some laboratory bridges which incorporate a variable capacitor have provision for making substitution measurements in this manner. The power factor or dissipation factor controls of such a bridge should be adjusted in the normal manner to sharpen the null.

Figure 1 (B) shows a resonant-type substitution circuit. Here, substitution capacitor C_t forms a series resonant tank circuit with inductor L_2. A trimmer capacitor (C_a) is connected in parallel with C_t. Audio-frequency or radio-frequency power is coupled into the tank through L_1. The resonance indicator (M) is a high-impedance v-t voltmeter. Resonance may be indicated also by an a-f or r-f milliammeter in series with C_t and L_2. In operation, C_t first is set to maximum capacitance (C_1) and trimmer C_a tuned to resonate the tank to the generator frequency, as indicated by peak deflection of meter M. The setting of C_a is not subsequently disturbed. Next, the unknown capacitor is connected to terminals X-X. This detunes the tank, as shown by decrease in the deflection. Finally, the setting of C_t is reduced to a capacitance (C_2) at which the tank again is tuned to resonance, as indicated by peak deflection of meter M. The unknown capacitance then is calculated: $C_x = C_1 - C_2$.

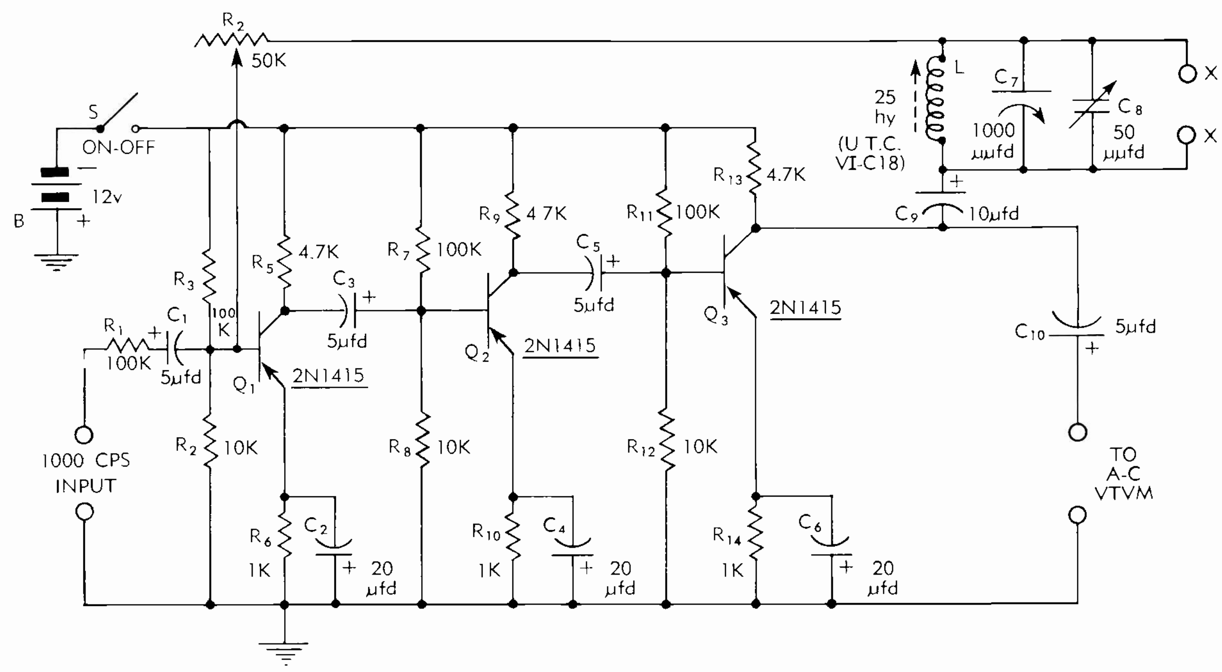
This type of substitution circuit is found in some r-f "reactance" meters and in twin-T measuring circuits.

Figure 1 (C) shows a similar circuit of the resonant type which also is usable at audio and radio frequencies and is adjusted in the same manner as explained for Figure 1 (B). The only difference is use here of a coupling resistor (R) instead of the inductive coupling of the preceding example. This resistance must be low, otherwise it will cause the circuit to tune broadly. Here again, the v-t voltmeter (M) may be replaced with a low-impedance a-f or r-f milliammeter connected in series with C_t and L. This type of circuit is found in some Q-meters.

It is easily seen that in each of the substitution circuits, the initial adjustment at C_t = maximum takes into account all stray capacitances in the measuring circuit. The capacitance removed from the circuit by readjustment of C_t after connection of C_x then is equal to C_x, and the corresponding simple remainder, $C_1 - C_2$, is not affected by the strays. In order to negate the effect of strays in leads to the unknown capacitor, the leads should be connected to X-X prior to the initial adjustment and should have the position and spacing they will when connected to the unknown.

The dial of the trimmer capacitor (C_a in Figures 1B and 1C) need not be calibrated, although it sometimes is made direct reading for small capacitance values (the maximum capacitance of C_a generally being smaller than that of C_t).

It is clear that either of the circuits shown in Figure 1 may be assembled from laboratory equipment. Thus for 1 (A), one miniature noninductive resistor (R_1), one potentiometer (R_2), one standard capacitor (C_3), one calibrated variable capacitor (C_t), one oscillator or signal generator, and one a-c vtvm are required. For 1 (B), one inductive coupler (L_1-L_2), one calibrated variable capacitor (C_t), one lower-capacitance trimmer (C_a) one v-t voltmeter (M) and one oscillator or signal



ALL RESISTORS ½ WATT

FEEDBACK CIRCUIT

Figure 5

After the oscillator has been set to 1 Mc, initially adjust the measuring circuit: (1) Set C_4 to maximum capacitance. (2) Set C_5 to mid range. (3) Adjust the slug of inductor L_4 for peak deflection of the meter (M). The slug setting should not subsequently be changed. Due to the low power output of the tunnel diode, the meter will not be deflected beyond full scale.

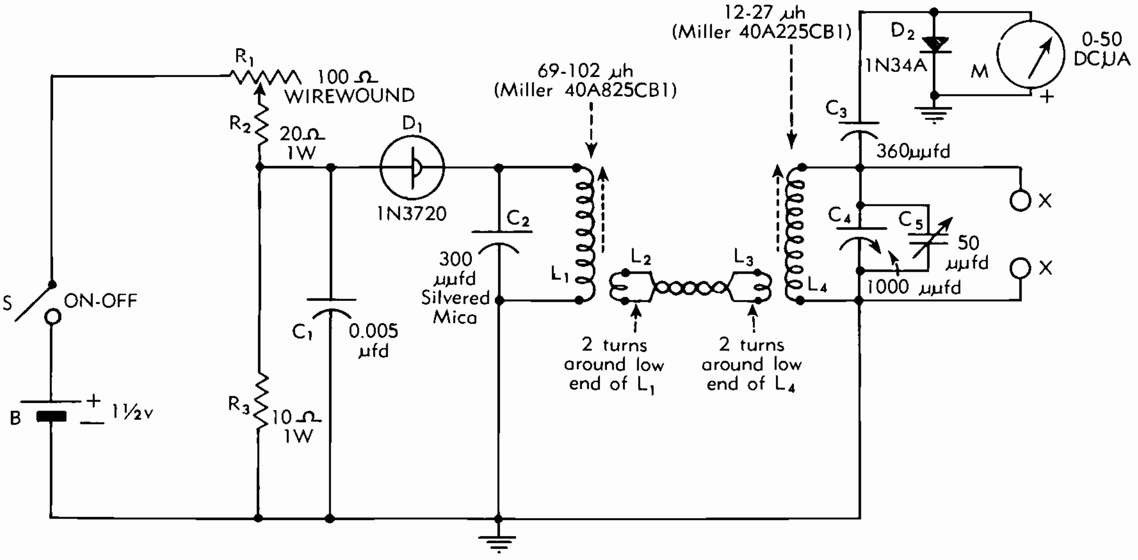
FEEDBACK CIRCUIT

Sharp tuning of the measuring circuit is afforded by the arrangement shown in Figure 5. The increased selectivity is obtained by including the measuring circuit (L-C_7-C_8) in the negative feedback loop around a 3-stage transistor audio amplifier. An external 1-kc oscillator supplies the test signal, and an external a-c vtvm serves as the indicator. Although a transistor circuit is shown here, a tube-type amplifier also may be used.

The circuit performs as a sharply tuned 1000-cps bandpass amplifier. The pass characteristic is obtained in this way: the negative feedback cancels the amplifier gain on all frequencies except 1000 cps, since the measuring circuit (acting as a high-Q wavetrap) removes this frequency. The amplifier accordingly passes 1000 cps and rejects all other frequencies outside of a narrow band. The 50,000-ohm rheostat (R_2) controls the feedback voltage applied to the input, hence acts as a selectivity control.

To adjust the circuit initially, (1) apply a 1-kc signal to the input terminals. (2) Connect an a-c vtvm to the output terminals. (3) Set C_7 to maximum capacitance. (4) Set C_8 to mid range. (5) Adjust the slug of inductor L for peak deflection of the meter. This setting should not subsequently be disturbed.

When using the circuit, adjust R_2 for desired sharpness of tuning.



TUNNEL DIODE CIRCUIT

Figure 4

The circuit is set initially in the following manner: (1) Inject a 1-kc or 1-Mc input signal, depending upon the selected value of L. (2) Set C_1 to maximum capacitance. (3) Set C_2 to mid range. (4) Adjust the tuning slug of inductor L for peak deflection of meter M. The oscillator output control may be adjusted to keep the deflection within the meter range.

TRANSISTOR CIRCUIT

Figure 3 shows the circuit of a completely self-contained substitution capacitance measuring set. This unit includes a 1-Mc transistor oscillator, substitution measuring circuit, and diode-type r-f milliammeter.

The oscillator is built around a 2N274 transistor (Q) operated from a self-contained 9-volt battery (B). The oscillator tank consists of slug-tuned inductor L_1 and silvered mica capacitor C_4. By means of the slug, the oscillator frequency may be set to 1 Mc with the aid of a frequency meter or calibrated radio receiver. Rheostat R_2 is the r-f output control.

The measuring circuit consists of inductor L_4, 1000-µµfd variable capacitor C_6, trimmer C_7, and an r-f milliammeter comprised by 1N56A germanium diode D and 0-50 d-c microammeter M. Energy is link-coupled from the oscillator into the measuring circuit by means of 2-turn coils L_2 and L_3.

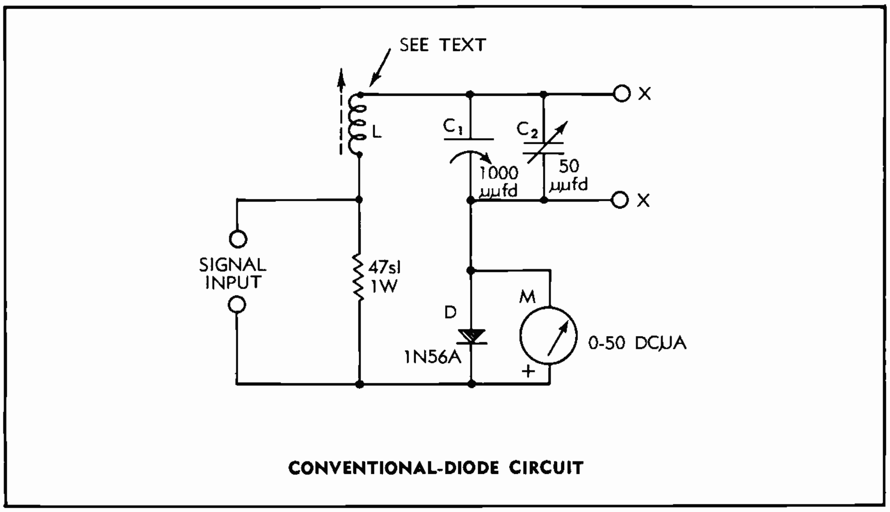
After the oscillator frequency has been set to 1 Mc, adjust the measuring circuit initially: (1) Set C_6 to maximum capacitance. (2) Set C_7 to mid range. (3) Adjust the L_4 slug for peak deflection of meter M. The slug setting should not subsequently be changed.

TUNNEL DIODE CIRCUIT

In the circuit shown in Figure 4, the 1-Mc oscillator uses a tunnel diode operated from a single 1½-v Size-D flashlight cell (B). This negative-resistance oscillator is unusually small and compact.

As in the preceding circuit, the oscillator tank is comprised by a 300-µµfd silvered mica capacitor (C_2) and slug-tuned inductor (L_1). Energy is link-coupled out of the oscillator into the measuring circuit by means of 2-turn coils L_2 and L_3. By adjusting the slug of L_1, the oscillator frequency may be set to 1 Mc with the aid of a frequency meter or calibrated radio receiver. To start the oscillator initially, close switch S and adjust rheostat R_1 for strongest oscillation, as indicated by peak deflection of an r-f vtvm temporarily connected across L_1. The setting of R_1 should not subsequently be changed unless the oscillator fails to start readily when the switch is closed.

The measuring circuit consists of inductor L_4, 1000-µµfd variable capacitor C_4, trimmer C_5, and an r-f voltmeter comprised by 1N34A germanium diode D_2, 0-50 d-c microammeter M, and 360-µµfd coupling capacitor C_3.



CONVENTIONAL-DIODE CIRCUIT

Figure 2

generator are required. And for 1 (C), one high-Q inductor (L), one noninductive coupling resistor (R), one calibrated variable capacitor (C_t), one lower-capacitance trimmer (C_a), one v-t voltmeter (M), and one oscillator or signal generator are required. In laboratory setups of this kind, the components must be rigidly mounted to prevent movement in relation to each other, and stray metallic objects should be removed from the field of coils.

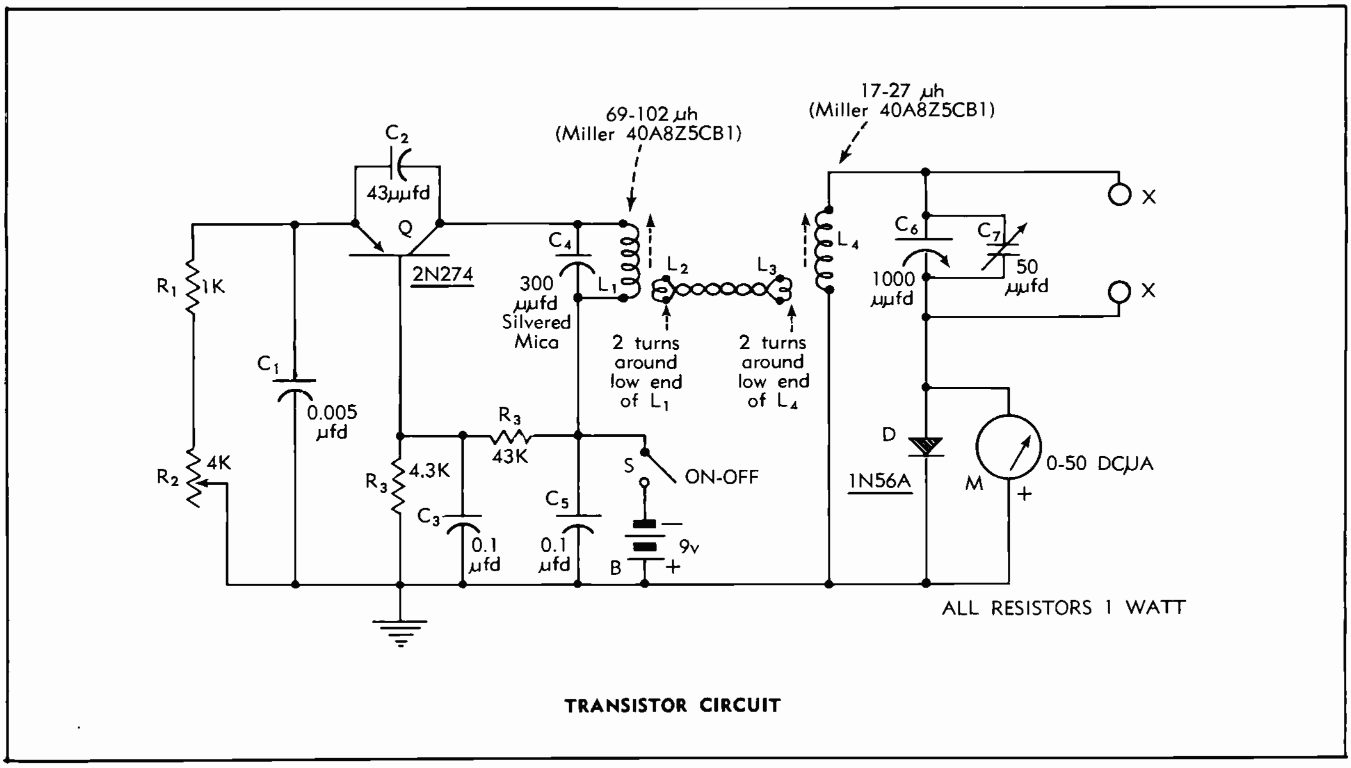
It is clear also that either of these circuits might be incorporated into a permanent instrument which would combine the signal source, measuring circuit, and indicating meter. The remainder of this article describes the circuits of several such instruments tested by the Editors, two of them consisting of measuring circuit and indicator only and two completely self-contained. These circuits cover the capacitance range 0-1000 μμfd, but this can be extended by using a suitable capacitor decade in place of the 1000-μμfd variable capacitor shown.

DIODE CIRCUIT

Figure 2 shows a measuring circuit with self-contained indicating meter. The only accessory needed is a signal generator. This may be a 1000-cps a-f oscillator or 1-Mc r-f oscillator.

Here, C_1 is the main capacitor (corresponding to C_t in the illustrative circuits in Figure 1) and C_2 is the trimmer. L is a 25-henry adjustable iron-core inductor (U. T. C. Type VI-C18) for 1000 cps, or an adjustable 25-μh inductor (Miller Type 40A225CB1) for 1 Mc. The indicator is a 0-50 d-c microammeter (M). The a-f or r-f tank current is rectified for this meter by 1n56A germanium diode D.

The external signal generator develops the test signal voltage across a 47-ohm 1-watt composition resistor (R). Approximately 1 volt rms will be required for full-scale deflection of meter M.



TRANSISTOR CIRCUIT

Figure 3

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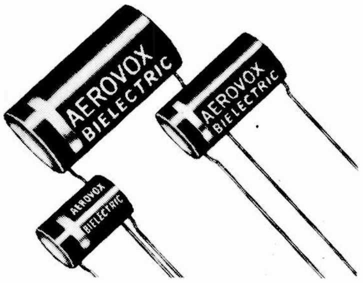

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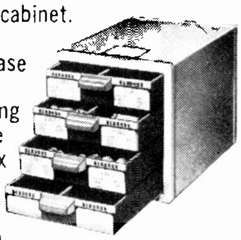

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