Radio Editors of magazines and newspapers are hereby given permission to reprint in whole or in part, with proper credit to the Aerovox Corporation, the contents of this issue of the Aerovox Research Worker.

The AEROVOX Research Worker

The Aerovox Research Worker is a monthly house organ of the Aerovox Corporation. It is published to bring the Radio Experimenter and Engineer authoritative, first hand information on condensers and resistances for radio work.

VOL. 17, NO. 9 SEPTEMBER, 1945

50c per year in U. S. A.
60c per year in Canada

Methods of Measuring Capacitor Q

By the Engineering Department, Aerovox Corporation

IT is convenient to express the efficacy of an inductor or capacitor in terms of its reactance to resistance ratio (X/R). This factor of merit, termed Q, is equal to 1/(6.28fCR) in the case of a capacitor. When capacitors are to be employed in radio equipment or in high-frequency electronic apparatus, radio-frequency Q values often are preferred to lower-frequency power factor readings as an indication of capacitor quality.

While the Q ratio is simple, the factor of merit itself cannot be determined readily by any simple means. A simple calculation of X/R is not possible, chiefly because of the difficulty, if not impossibility in most cases, of fixing precisely the value of R. R represents not only the d. c. resistance, but also the combined effect of any other in-phase components which have the same effect as pure resistance. Such components are caused by skin effect in all conductors in the capacitor, presence of dielectric material within the electrostatic field, contact resistance and by numerous other similar causes. The actual value of R at radio frequencies often is several decades to several hundred times the d.c. resistance, and is not measurable directly as resistance by means of any simple instrument. The most important R component is capacitor work shows up as *series* resistance.

When the first problem is to determine the value of high-frequency resistance, it is customary to measure the Q, and to find the value of equivalent series resistance by means of the equation:

$$R = \frac{1}{6.28\,C\,Q} \qquad (1)$$

or some form of this relationship. Figure 1 is a chart showing 1-megacycle values of equivalent series resistance of capacitors having various Q values between 100 and 1000. Q and R are listed for nineteen standard capacitance values between 0.001 and 0.01 mfd. The utility of this chart may be extended by applying the following rules:

1. To find R corresponding to a 1-Mc. Q higher than 100, but not shown in the chart. Multiply the R value in the Q-100 column by $100/Q_X$, where Q_X is the higher Q value.
2. To find R corresponding to a 1-Mc. Q lower than 100. Multiply the R value in the Q-100 column by $Q_X/100$, where Q_X is the lower Q value.
3. To find 1-Mc. R for any capacitance lower than 0.001 mfd. Locate opposite 0.001 mfd. in the chart the R value corresponding to the Q of the sample capacitor, applying Rule 1 or Rule 2 if necessary. Multiply this R value by $0.001/C_X$, where C_X is the low capacitance value in mfd.
4. To find R for any capacitance higher than 0.001 mfd., but not shown in the chart. Locate opposite 0.001 mfd. in the chart the R value corresponding to the Q of the sample capacitor, applying Rule 1 or Rule 2 if necessary. Multiply this R value by $C_X/0.001$, where C_X is the higher capacitance value in mfds.
5. To find R at any frequency higher or lower than 1 megacycle. Having determined the Q value of the capacitor at 1 Mc., find the R value by means of the chart, using any one or more of the first four rules if necessary. Multiply this R value by f_X, where f_X is the new frequency in megacycles.

By appropriate combination of these rules, the chart given in Figure 1 may be employed to determine the equivalent series resistance of any capacitor, showing any Q value at any frequency.

CAPACITOR Q MEASUREMENT METHODS

Theoretically at least, any radio-frequency instrument capable of indicating the reactive and resistive (or conductive) components of a capacitor current and the values of X

FIG. 1 1-Mc. VALUES OF EQUIVALENT SERIES RESISTANCE (R)

CAP. (mfd.)	Q 100	Q 150	Q 200	Q 250	Q 300	Q 350	Q 400	Q 450	Q 500	Q 550	Q 600	Q 650	Q 700	Q 750	Q 800	Q 850	Q 900	Q 950	Q 1000
0.001	1.591	1.061	0.795	0.636	0.530	0.455	0.398	0.354	0.318	0.290	0.265	0.245	0.227	0.212	0.199	0.187	0.177	0.167	0.159
0.0015	1.061	0.708	0.531	0.425	0.354	0.303	0.268	0.236	0.212	0.193	0.177	0.163	0.152	0.141	0.133	0.125	0.118	0.112	0.106
0.002	0.795	0.530	0.398	0.318	0.265	0.227	0.198	0.177	0.159	0.145	0.133	0.122	0.114	0.106	0.0993	0.0936	0.0884	0.837	0.0795
0.0025	0.636	0.424	0.318	0.254	0.214	0.182	0.159	0.141	0.127	0.116	0.106	0.0978	0.091	0.085	0.0795	0.075	0.0706	0.067	0.0636
0.003	0.530	0.354	0.265	0.212	0.177	0.151	0.133	0.118	0.106	0.0965	0.0884	0.0815	0.0758	0.0706	0.0663	0.0624	0.0589	0.0558	0.053
0.0035	0.455	0.304	0.228	0.182	0.152	0.130	0.114	0.101	0.091	0.0827	0.0759	0.0700	0.0650	0.0606	0.0569	0.0536	0.0505	0.0479	0.0455
0.004	0.398	0.256	0.198	0.159	0.133	0.114	0.0995	0.0885	0.0796	0.0724	0.0664	0.0613	0.0569	0.0531	0.0497	0.0469	0.0443	0.0419	0.0398
0.0045	0.354	0.236	0.177	0.142	0.118	0.101	0.0886	0.0787	0.0709	0.0644	0.0591	0.0545	0.0506	0.0473	0.0443	0.0417	0.0394	0.0373	0.0354
0.005	0.318	0.212	0.159	0.127	0.106	0.0909	0.0795	0.0707	0.0636	0.0579	0.0530	0.0490	0.0455	0.0424	0.0398	0.0374	0.0354	0.0335	0.0318
0.0055	0.290	0.193	0.145	0.116	0.0967	0.0829	0.0725	0.0645	0.0580	0.0528	0.0483	0.0446	0.0415	0.0387	0.0362	0.0341	0.0322	0.0306	0.0290
0.006	0.265	0.177	0.132	0.106	0.0884	0.0757	0.0663	0.0589	0.0530	0.0482	0.0442	0.0408	0.0378	0.0354	0.0331	0.0312	0.0294	0.0279	0.0265
0.0065	0.245	0.163	0.122	0.0980	0.0816	0.0700	0.0613	0.0545	0.0490	0.0445	0.0408	0.0377	0.0350	0.0326	0.0306	0.0288	0.0272	0.0258	0.0245
0.007	0.227	0.151	0.114	0.0908	0.0757	0.0649	0.0567	0.0504	0.0454	0.0413	0.0378	0.0350	0.0324	0.0301	0.0284	0.0267	0.0252	0.0239	0.0227
0.0075	0.212	0.141	0.106	0.0849	0.0706	0.0606	0.0530	0.0472	0.0424	0.0386	0.0354	0.0326	0.0303	0.0283	0.0265	0.0249	0.0236	0.0224	0.0212
0.008	0.199	0.133	0.0996	0.0796	0.0664	0.0569	0.0497	0.0442	0.0398	0.0362	0.0332	0.0306	0.0284	0.0266	0.0249	0.0232	0.0221	0.0209	0.0199
0.0085	0.187	0.125	0.0935	0.0749	0.0624	0.0534	0.0468	0.0416	0.0374	0.0340	0.0312	0.0288	0.0267	0.0249	0.0234	0.0220	0.0208	0.0197	0.0187
0.009	0.177	0.118	0.0885	0.0708	0.0590	0.0506	0.0443	0.0393	0.0354	0.0322	0.0295	0.0272	0.0253	0.0236	0.0222	0.0208	0.0197	0.0186	0.0177
0.0095	0.167	0.111	0.0835	0.0668	0.0556	0.0477	0.0417	0.0371	0.0334	0.0304	0.0278	0.0257	0.0238	0.0223	0.0209	0.0197	0.0186	0.0176	0.0167
0.01	0.159	0.106	0.0795	0.0636	0.0530	0.0455	0.0398	0.0354	0.0318	0.0290	0.0265	0.0245	0.0227	0.0212	0.0199	0.0187	0.0177	0.0167	0.0159

and R or G (conductance, 1/R) may be used for capacitor Q determinations. These instruments include mainly radio-frequency bridges and T-networks. The values of X and R obtained by such measurement may be substituted in the Q ratio X R, or in the Q product XG.

Actually, the instruments referred to and generally available do not usually possess the high degree of sensitivity required for close determination of "nearby" Q values, especially when these values are high. Nor do they operate over a sufficiently wide capacitance range to be completely useful.

The Q-meter, which in the conventional form makes use of a resonant radio-frequency tank circuit, is the most widely used and accepted instrument for capacitor Q measurements. Q-meters, whether specifically manufactured as such or assembled for temporary use from laboratory components, employ one of two schemes — the *Q-voltmeter method* or the *susceptance variation method.*

Q-VOLTMETER METHOD

In this scheme, radio-frequency energy is coupled into a tank circuit which is resonated by means of a variable air capacitor both with and without the test capacitor in the circuit, and the r. f. voltage across the capacitor is measured in each case. R. f. input to the measuring circuit is kept constant.

Such a scheme is illustrated by Figure 2-A. R. f. voltage from the oscillator is applied across the resistor R, which is connected in series with the tuned-circuit components. This resistance is very low, being of the order of 0.05 ohm. Voltage across the coupling resistor is held constant for all tests by adjusting the oscillator output control for a reference deflection of the thermogalvanometer. Values of coil L and tuning capacitor C_T have so been chosen that the L-C circuit may be resonated to the oscillator frequency.

If an r. f. voltage "e" is introduced into the tuned circuit in the manner indicated by the circuit diagram, the voltage across the capacitor will be proportional to the Q of the tuned circuit. The Q of the variable air capacitor will be infinite if this is a first-grade component, and the r. f. voltage indicated by the v. t. voltmeter accordingly will be proportional to the Q of the sample fixed capacitor, C_X, in the circuit.

Assuming the circuit to be resonated with the test capacitor in place, Q of the circuit will be indicated by the ratio of the r. f. voltage (E) across the capacitor at resonance to the voltage (e) applied to the circuit. Q = E/e. The v. t. voltmeter thus may be graduated directly in Q units. Figure 3 shows the Q values corresponding to voltage deflections of a 0-5 v. scale v. t. voltmeter. These values are based upon an oscillator current of 0.4 ampere, which will develop 20 m. v. across resistor R (Figure 2).

However, values obtained in this manner are of *effective* Q of the tuned circuit which differs markedly from true capacitor Q. The capacitance of the capacitor being tested must be taken into consideration in a determination of true Q.

The Q-voltmeter method of measuring true capacitor Q consists of resonating the measuring circuit both with and without the test capacitor (C_X), noting capacitance settings of the variable capacitor (C_T) in each case, and the effective Q readings as shown by the v. t. voltmeter (Figure 3) in each case. A relatively simple calculation involving these data then will yield the true Q value.

Since, in order to resonate the circuit the second time, that is with C_X in place (See Figure 2-A), it becomes necessary to "detune" C by the amount of the extra capacitance introduced into the circuit by C_X, it follows that the capacitance range of C_T must be equal at least to the capacitance of C_X to be tested. The capacitance range of C_T thus imposes a limitation upon the maximum capacitance of sample units which may be tested by the arrangement shown in Figure 2-A. Capacitors having capacitances in excess of the maximum value of C_T may be tested for Q, however, provided they are placed in series with L and C_T as shown in Figure 2-B. In order to resonate initially this latter circuit, C_X must temporarily be replaced by a low-impedance short-circuiting bar.

The Q-voltmeter method thus includes two methods of measurement — *series circuit* and *parallel circuit.*

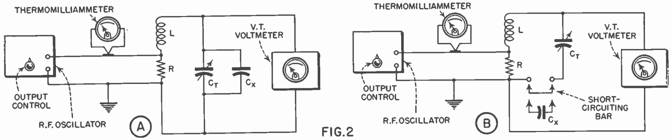

FIG.2

Series Method. (Figure 2-B). The Q readings are taken directly from the v. t. voltmeter Q scale (See Figure 3). C readings are taken directly from the C settings. C_1 and Q_1, correspond to the intial resonating of the measuring circuit, without the test sample. C_2 and Q_2 correspond to the final resonating with the test sample in the circuit. True Q is determined from these data by means of the equation:

$$Q = \frac{(C_2 - C_1)\,Q_1 Q_2}{C_1 Q_1 - C_2 Q_2} \qquad (2)$$

Parallel Method. (Figure 2-A). Here also, C_1 and Q_1 are readings taken from the initial setting of the circuit to resonance without the test sample, C_2 and Q_2 from final settings with C_X in place. True Q is determined from these data by means of the equation:

$$Q = \frac{(C_1 - C_2)\,Q_1 Q_2}{C_1 (Q_1 - Q_2)} \qquad (3)$$

SUSCEPTANCE VARIATION METHOD

In this method, commonly called the "band-width method", a radio-frequency voltage is coupled, usually by means of very loose magnetic coupling, into a series resonant circuit containing a coil, L, of very high Q and the capacitor C_X which is under test.

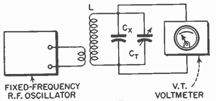

FIG.5

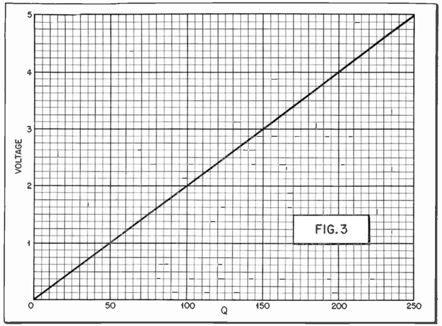

FIG.3

In the first scheme of the susceptance variation method (See Figure 4), a variable-frequency r. f. oscillator is employed. The v. t. voltmeter deflection (e) at resonance (f_r) is noted. The oscillator then is detuned to a frequency (f_1) below resonance at which the v. t. voltmeter deflection falls to 70.7% of e. The oscillator finally is detuned to a point (f_2) above resonance at which the v. t. voltmeter deflection again falls to 0.707e.

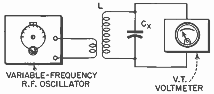

FIG.4

Q may then be determined from these data by means of the equation:

$$Q = \frac{f_r}{f_2 - f_1} \qquad (4)$$

In the second scheme (See Figure 5), a fixed-frequency r. f. oscillator is employed, and a variable air capacitor (C_T) having infinite Q is included in parallel with L and C_X. C_T is adjusted to a capacitance setting (C_r) for resonance, and the v. t. voltmeter deflection (e) is noted. C_T then is detuned to a point (C_1) below resonant capacitance at which the meter deflection falls to 0.707e. C_T finally is detuned to another point (C_2) above resonant capacitance at which the meter deflection again falls to 0.707e.

Q then may be determined from these data by means of the equation:

$$Q = \frac{2C_r}{C_2 - C_1} \qquad (5)$$

At the points along the circuit resonance curve where the v. t. voltmeter deflection drops to 70.7% of its resonant value, the circuit reactance is equal to the circuit resistance: ($X = R$). At this point, the circuit impedance $Z = \sqrt{2}\,R$. At resonance, the total circuit reactance is zero, and $Z = R$.

The voltage ratio has been determined from the ratio of currents in the circuit at resonance and at a point where $X = R$. These currents are equal to E/R at resonance, and to $E/(\sqrt{2}\,R)$ at the point where $X = R$. The current ratio is:

$$\frac{\dfrac{E}{\sqrt{2}\,R}}{E/R} = \frac{1}{\sqrt{2}} = 0.707 \qquad (6)$$

which is the factor by which the original (resonant) voltmeter deflection is multiplied to indicate the point at which X = R

Application of the susceptance variation method to measurement of capacitor Q is limited to Q values lower than the Q of coil L, since the latter would tend to mask higher capacitor Q values.