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# "Connector-Pair" Techniques for the Accurate Measurement of Two-Terminal Low-Value Capacitances

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A method is described that allows two-terminal capacitance measurements to be performed with uncertainties of $\pm 0.0001-0.0002$ pF, the ultimate accuracy limit being imposed only by the repeatability performance of the connectors. This technique has been used for the calibration of coaxial capacitance standards and the measurement of the fringe capacitance of coaxial open-circuit terminations; other applications are also possible in the field of high-frequency coaxial measurements.

Key words: Capacitance measurement; coaxial adaptor; coaxial connector; fringe capacitance; standard capacitor; two-terminal capacitor.

## 1. Introduction

Two-terminal capacitance standards of relatively low nominal value (beginning with 1 pF), equipped with coaxial connectors, are often used in high frequency measurements. Such capacitors are currently manufactured as working standards for calibrating impedance bridges. Coaxial precision capacitors are the most suitable reference standards for a general system of high frequency immittance calibration [1].[2] There is therefore an increasing need for accurate calibration of these capacitance standards.

Generally, precision standard capacitors intended for high frequency operation are calibrated at a low frequency and a frequency dependent correction is separately evaluated for taking into account the effect of the residual inductance [2]. Thus, the final accuracy of the capacitor calibration is to a great extent (and sometimes almost entirely) determined by the accuracy of the low frequency measurement. The main difficulty in this measurement is to establish a precise reference plane separating the capacitor from the measuring circuit. This plane must be mechanically identifiable and precisely reproducible; the capacitance measurement will be repeatable only in this case, avoiding the "connection errors." The best presently known way to meet these requirements is to equip both the capacitor and the measuring instrument with precision coaxial connectors [3].

It is generally accepted that the effective capacitance of a standard two-terminal capacitor is the capacitance added to the measuring circuit when the capacitor is connected to the terminals of the instrument (usually a bridge). It must be assumed that before connecting the capacitor, the instrument terminals were in a conventionally adopted "reference state," for example in open-circuit, with a special open-circuit termination or in a hypothetical radial-field (TEM-field) configuration. The latter convention is to be preferred, since it gives a definition of the capacitance independent of the bridge terminals. The capacitance is defined assuming (a) a radial field in the vicinity of the connector reference plane and (b) the capacitor electrodes limited by the connector reference plane. In principle, this definition gives a precise meaning to the two-terminal capacitance concept, making it independent of the instrument used for its measurement. Two techniques have been developed for the measurement of two-terminal capacitance, in accordance with this definition:

(a) The measurement is performed in two steps, first balancing the bridge with terminals open-circuited and then rebalancing with the capacitor connected. The result is:

$$C_x = \Delta C_m + C_f$$

where $\Delta C_m$ is the difference between the two readings on the bridge and $C_f$ is the fringe capacitance of the open-circuit connector [4]. Special techniques are required to determine the value of $C_f$ with a satisfactory accuracy.

(b) A three-terminal to two-terminal adaptor, equipped with a suitable output connector, is inserted between a three-terminal bridge and the capacitor.

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[2] Figures in brackets indicate the literature references at the end of this paper.



403-833 O - 70 - 4

The capacitance to be determined is:

$$C_x = C_m - C_{\mathrm{ad}}$$

where $C_m$ is the measured total direct capacitance and $C_{\mathrm{ad}}$ is the direct capacitance of the adaptor. This method has been developed at the National Bureau of Standards [2]; the adaptor is of a coaxial guard-electrode type, and $C_{\mathrm{ad}}$ was calculated in terms of the dimensions of the active section.

Both methods have the disadvantage that their accuracy depends directly on the accuracy with which the values of $C_f$ and $C_{\mathrm{ad}}$ respectively are known. Experience has shown that good quality connectors allow a very good repeatability to be achieved; nonrepeatability errors are typically one order of magnitude smaller than the uncertainty of $C_f$ and $C_{\mathrm{ad}}$. Therefore, existing techniques are limited to an accuracy considerably lower than the precision attainable in two-terminal capacitance measurements by using precision coaxial connectors.

The "connector-pair" techniques described here require no corrections to be made nor any fringe capacitances or adaptor capacitances to be known. Two coaxial cables are used, each terminated with a precision connector of the same type as the capacitor to be measured. The capacitance is measured successively with each of these cables. The unknown capacitances of the cable and connector are then eliminated by connecting both cables to the bridge and making an additional measurement with the cable connectors coupled together. To avoid errors due to capacitance changes when cables are curved, a three-terminal bridge is used and the cable outer conductors are connected to the ground terminal of the bridge. Simple, non-precision two-terminal to three-terminal adaptors are introduced to connect the capacitor to the coaxial cables.

Thus, the measuring circuit contains only connector pairs; in each measurement, two of the three connectors involved are coupled together, in all possible combinations. Obviously, an essential condition for this is the sexless character of connectors.

The same principle can be applied in other measurements encountered in high frequency coaxial measurements: for example, determination of the direct capacitance of precision three-terminal to two-terminal adaptors, fringe capacitance measurements of precision coaxial connectors and measurement of the capacitance of precision coaxial lines.

## 2. Two-Terminal Capacitance Measurement

The measuring arrangement is shown in figure 1.

The capacitor, whose capacitance $C_x$ is to be measured, is connected to the output of a three-terminal to two-terminal adaptor. This adaptor has been simply improvised by combining two NBS-Woods type coaxial connectors [5] with a thin dielectric sheet introduced between the outer conductor flanges.[3] A precision transformer-arm bridge is used, in three-terminal connection. Therefore, the measured capacitance is composed of $C_x$ and the direct capacitance of the adaptors, $C_A$ and $C_B$ respectively.

The measurement procedure is as follows:

(a) The first adaptor with its cable and the capacitor $C_x$ are connected to the bridge terminals (fig. 1a); the capacitance measured by the bridge is

$$C_1 = C_A + C_x \tag{1}$$

(b) Introducing the second adaptor into the circuit (fig. 1b) the measured capacitance is

$$C_2 = C_B + C_x \tag{2}$$

(c) Finally, with both adaptors connected to the bridge and their output connectors coupled together (fig. 1c) one obtains

$$C_3 = C_A + C_B. \tag{3}$$

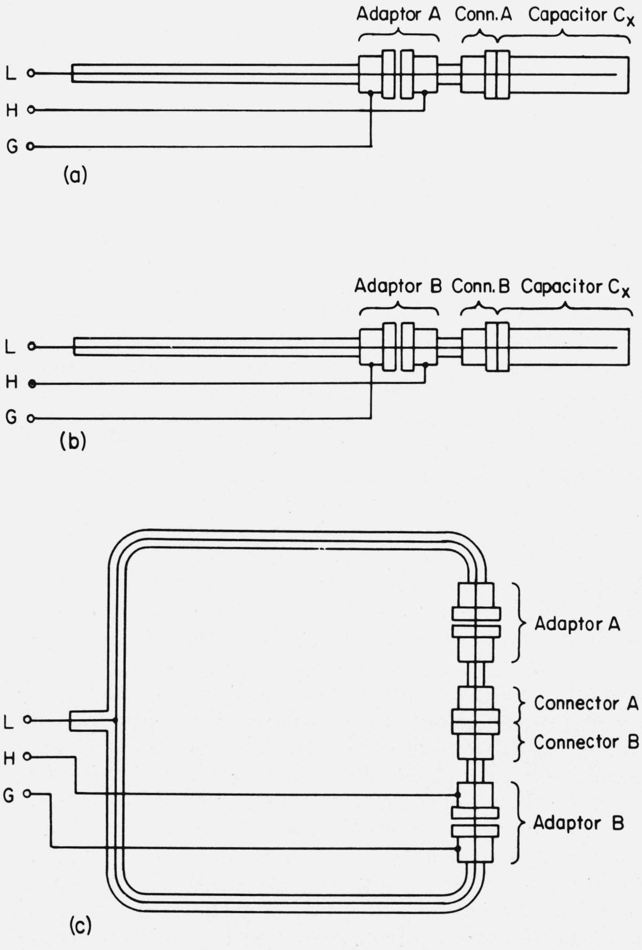


FIGURE 1. *"Connector-pair" technique for two-terminal capacitance measurement:* (a) *First adaptor with capacitor connected to the bridge;* (b) *Second adaptor with capacitor connected to the bridge;* (c) *Both adaptors connected, with connectors coupled together.*
L—"low"-terminal of the bridge (detector input); H—"high"-terminal of the bridge (transformer output); G—"ground"-terminal of the bridge.

[3] Any other types of such adaptors can be used, the only conditions being a rigid construction and good shielding.

Thus, from (1), (2) and (3):

$$C_x = \frac{1}{2}(C_1 + C_2 - C_3). \tag{4}$$

It is seen that the value of $C_x$ is simply given by combining three measured capacitance values. In all cases there are only coupled connectors in the measuring circuit, thus assuring the required radial field conditions in the zone of the connector reference planes. In this way, the capacitor is connected in the normal manner and the radial field condition is achieved without using any extraneous devices.

The capacitance of five standard two-terminal capacitors, of nominal values ranging from 1 pF to 5 pF, was measured by this method. All capacitors and adaptors were equipped with 14 mm precision coaxial connectors. Each measurement was carried out at least ten times; generally, the repeatability was within ± 0.0001 pF and in a few cases within ± 0.0002 pF, except the 5 pF capacitor which exhibited a larger spread of the measured values.

Measurements were repeated using different adaptors (at least six adaptors in each case); no significant changes of the measured $C_x$ values were noticed. However, care had to be taken to avoid imperfect coupling of connectors; in view of this, all measurements were repeated with connectors joined in two or three different positions.

For comparison, the capacitors were calibrated by using the three-terminal to two-terminal adaptor method [2]. In these measurements, the value of the direct capacitance of the NBS precision adaptor was taken as $C_{ad} = 0.8528$ pF (see next section). Values determined by the two methods agree within the uncertainties of both methods.

The results are summarized in table 1. The "estimated measurement uncertainty" includes nonrepeatability errors, systematic errors due to mechanical imperfections of individual connectors and errors introduced by the bridge. In most cases, errors caused by connector imperfections and bridge errors were negligible, so that the uncertainty figures given in table 1 practically coincide with the nonrepeatability values mentioned above; these figures represent an estimation based on computations of $3\sigma$ (three times the standard deviation).

TABLE 1. *Measured capacitance of two-terminal capacitance standards*

| Nominal value pF | Measured value pF | | Estimated measurement uncertainty pF |
|---|---|---|---|
| | By the method described | By the "adaptor" method | |
| 1 | 1.0007 | 1.0007 | ±0.0001 |
| 2 | 2.0014 | 2.0013 | ±.0002 |
| ................ | 2.6675 | 2.6675 | ±.0001 |
| ................ | 2.6690 | 2.6691 | ±.0002 |
| 5 | 4.999 | 4.999 | ±.001 |

## 3. Measurement of the Direct Capacitance of Precision Three-Terminal to Two-Terminal Adaptors

The same technique allows the direct capacitance of a three-terminal to two-terminal adaptor to be accurately measured. For this purpose, the adaptor is subjected to a measurement procedure similar to that previously described, together with two auxiliary three-terminal to two-terminal adaptors. Each adaptor pair is successively introduced in the circuit shown in figure 1c; the following equations are obtained:

$$C_1 = C_{ad} + C'_{ad}; \tag{5}$$

$$C_2 = C_{ad} + C''_{ad}; \tag{6}$$

$$C_3 = C'_{ad} + C''_{ad}; \tag{7}$$

where: $C_1$, $C_2$, and $C_3$ are the measured capacitance values, $C_{ad}$ is the direct capacitance of the adaptor to be measured and $C'_{ad}$, $C''_{ad}$ are the direct capacitances of the auxiliary adaptors.

Equations (5), (6), and (7) give

$$C_{ad} = \frac{1}{2}(C_1 + C_2 - C_3). \tag{8}$$

One of the auxiliary adaptors may be replaced by a simple coaxial capacitor. In this case, the measurement is performed following step by step the procedure illustrated in figures 1a, 1b, and 1c.

More than two auxiliary adaptors may be also used, in all possible combinations, to obtain a number of equations exceeding the number of unknown quantities (for example, in the case of three auxiliary adaptors, 6 equations may be written for $C_{ad}$, $C'_{ad}$, $C''_{ad}$, and $C'''_{ad}$). The use of more than three auxiliary adaptors permits determination of the same adaptor capacitance by a number of different combinations and, thereby, reveals any systematic errors which may exist.

The direct capacitance of the NBS precision two-terminal to three-terminal coaxial adaptor [2] was determined by this method. Six auxiliary adaptors were used, in various combinations. As in the previously described measurements, the repeatability was within ±0.0001 pF; no significant systematic errors could be detected.

The value obtained is

$$C_{ad} = 0.8528 \pm 0.0002 \text{ pF},$$

the estimated uncertainty including adaptor and connector instabilities.

The value previously determined by calculation, based on dimensional measurements, is

$$C_{ad} = 0.8513 \text{ pF}.$$

## 4. Connector Fringe Capacitance Measurements

The fringe capacitance of precision coaxial connectors has an important role in both lumped and distributed parameter measurements. For certain configurations this fringe capacitance may be calculated. A high frequency method for measuring the fringe capacitance of precision coaxial connectors was described by Woods [4] and a low frequency one by Hersh [6]. The high frequency method consisted of measuring the difference of connector capacitances with open end and terminated by a precision quarter-wavelength short-circuited line. The low frequency method was based on three-terminal measurements with a guard electrode, an insulating gap being inserted in either the inner or the outer conductor of the coaxial connector. Both methods are rather cumbersome and of a limited accuracy, primarily because of certain perturbing effects that must be evaluated (for example, the "short-circuit" end of the $\lambda/4$ line, the insulating gap separating the guard electrode).

The "connector-pair" technique is particularly suitable for accurate fringe capacitance measurements, since the connector is under normal working conditions and no corrections or estimations are to be made.

Consider the measuring circuit shown in figure 2a,

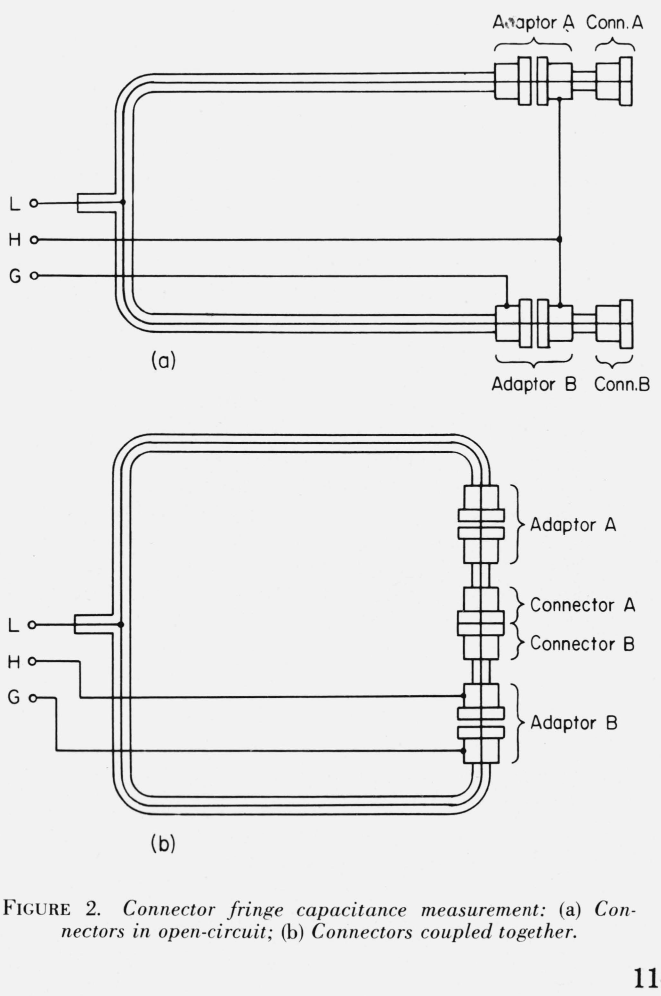


FIGURE 2. *Connector fringe capacitance measurement:* (a) *Connectors in open-circuit;* (b) *Connectors coupled together.*

similar to that previously described. The measured capacitance is

$$C_1 = C_A + C_{fA} + C_B + C_{fB} \tag{9}$$

where $C_A$ and $C_B$ are the direct capacitances of the adaptors, and $C_{fA}$ and $C_{fB}$ are the fringe capacitances of connectors at adaptor outputs.

Now, if the connectors are coupled together, as in figure 2b, fringe capacitances disappear and the bridge measures

$$C_1' = C_A + C_B. \tag{10}$$

From (9) and (10) the sum of the fringe capacitances is

$$C_{dA} + C_{fB} = C_1 - C_1' = \Delta C_1. \tag{11}$$

Having three adaptors, with the same type of output connectors, these measurements can be performed three times, taking successively every possible combination of two connectors. The resulting equations

$$\begin{aligned} C_{fA} + C_{fB} &= \Delta C_1; \\ C_{fB} + C_{fC} &= \Delta C_2; \\ C_{fC} + C_{fA} &= \Delta C_3; \end{aligned} \tag{12}$$

give the following expressions for the fringe capacitances:

$$\begin{aligned} C_{fA} &= \frac{1}{2}(\Delta C_1 - \Delta C_2 + \Delta C_3); \\ C_{fB} &= \frac{1}{2}(\Delta C_1 + \Delta C_2 - \Delta C_3); \\ C_{fC} &= \frac{1}{2}(-\Delta C_1 + \Delta C_2 + \Delta C_3). \end{aligned} \tag{13}$$

Therefore, the fringe capacitance of any coaxial connector (only sexless) can be determined by connecting it to the output of a three-terminal to two-terminal adaptor and by using two other auxiliary adaptors to perform the three measurements described. More than two auxiliary adaptors may also be used, in all possible combinations, to obtain a redundant system of equations that reduces measurement uncertainties.

Table 2 shows the measured values of fringe capacitances on several 14 mm precision coaxial connectors.

The fringe capacitances were determined in two cases: connectors with a special open-circuit termination and without termination (open end). Larger uncertainties in open-end condition take account of noncontrollable influence of surrounding objects.

It may be seen that for each individual connector the value of the fringe capacitance is quite stable, the measurements giving repeatable results. However, there is a relatively large spread of the $C_f$ values for different connectors of the same type. It is believed that the value of $C_f$ depends primarily on the location

TABLE 2. *Measured values of the fringe capacitance of 14 mm precision connectors*

| Connector | With special open-end termination | | Open-end | |
|---|---|---|---|---|
| | Fringe capacitance pF | Uncertainty pF | Fringe capacitance pF | Uncertainty pF |
| No. 2 | 0.1662 | ±0.0002 | 0.1484 | ±0.001 |
| No. 5 | .1672 | ±.0002 | .1490 | ±.001 |
| No. 9 | .1625 | ±.0002 | .1452 | ±.001 |
| No. 10 | .1696 | ±.0002 | .1513 | ±.001 |
| NBS adapt. | .1655 | ±.0002 | .1480 | ±.001 |

of the center conductor top with respect to the reference plane. With different terminations, $C_f$ values are practically unchanged (variations noticed were smaller than 0.0001 pF).

The measured values of $C_f$ are generally lower than indicated in the literature [7] for this type of connector: 0.172±0.008 pF with the special open-circuit termination and 0.155±0.008 pF with open end.

## 5. Measurement of the Capacitance of Two-Port, Four-Port or Six-Port, Precision Coaxial Devices

The capacitance of two-port, four-port, or six-port coaxial devices such as precision coaxial lines, angles, ramifications, cubes, etc., can be also determined by this method. In every case, the capacitance is measured under rigorous radial field conditions for all ports of the device.

The total capacitance of a precision coaxial line may be measured by inserting the line between the coaxial connectors of two three-terminal to two-terminal adaptors. The line capacitance value is simply obtained by substracting the sum of the adaptor direct capacitances, measured with the adaptor connectors coupled together. This technique avoids errors due to inequalities of connector fringe capacitances, occuring in conventional methods based on open-circuit terminations.

The capacitance of a precision 50 Ω line of 10 cm length with 14 mm connectors at both ends was measured, using several pairs of adaptors in the measuring circuit. The value obtained was 6.6683±0.0005 pF.

## 6. Some Remarks Concerning the Measurement of Small Capacitances With Two-Terminal Bridges

Most two-terminal bridges require an initial balance (or "zero adjustment") which is commonly performed with open terminals. As long as the measured capacitance value is relatively large or the accuracy required is low, the effect of the fringe capacitance of the bridge terminals is usually neglected, and the "initial balance capacitance" is conventionally taken as zero. In precision measurements of low-value capacitances, however, this effect can be important and the initial balance must be related to a precisely known capacitance value. The most simple possibilities are to use for the initial balance either an open-circuit termination or a standard low-value two-terminal capacitor.

As previously mentioned, fringe capacitance values of precision coaxial connectors vary within relatively wide limits (table 2). However, the capacitance of a standard coaxial capacitor is quite stable and free of connector errors. In other words, the capacitance added to the measuring circuit by an open-circuit termination depends upon the connector; even for the same type of connector, a spread of ±0.01 pF may occur from one individual connector to another, while the capacitance added to the measuring circuit by a coaxial capacitor is practically independent of the bridge terminal connector. Consequently, it is better technique to use a small value standard capacitor for the initial balance of a two-terminal bridge (or, in general, a two-terminal capacitance measuring instrument) than an open-circuit termination.

For example, consider the case of a two-terminal bridge with a 14 mm precision connector. If a 1 pF standard capacitor is used, the initial balance can be performed in a simple way, with an accuracy of typically ±0.001 pF or better. If an open-circuit termination were used instead, (a) the initial balance would correspond to a fractional capacitance value (equal to the fringe capacitance of the bridge terminal connector) and (b) this value would be variable from one bridge to another, typically between 0.16 pF and 0.17 pF.

When two-terminal capacitances are measured by a substitution method, connecting to the bridge the capacitor to be measured and then a standard capacitor of the same nominal value, the bridge serves only for determining the small difference between the two capacitance values. In this case there is no need for an additional initial bridge balance.

## 7. Conclusions

The "connector-pair" technique described offers a relatively simple way to increase the accuracy of two-terminal low-value capacitance measurements up to the limits imposed by the connectors themselves. The main application of this technique is in calibration of coaxial impedance standards. However, capacitance being one of the electrical quantities measurable with the highest accuracy, other applications are also possible, in the field of high frequency measurements, transducers, etc.

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## 8. References


[1] Huntley, L. E., and Jones, R. N., Lumped parameter impedance measurements, Proc. IEEE **55**, No. 6, 900–911 (June 1967).

[2] Jones, R. N., and Huntley, L. E., A precision, high frequency calibration facility for coaxial capacitance standards, Nat. Bur. Stand. (U.S.), Tech. Note 386, 27 Pages (March 1970).

[3] Jones, R. N., and Huntley, L. E., Precision coaxial connectors in lumped parameter immitance measurements, IEEE Trans. on Instrumentation and Measurements **IM–15**, No. 4, 375–380 (Dec. 1966).

[4] Woods, D., A coaxial connector system for precision R.F. measuring instruments and standards, Proc. IEE (London) **108 B**, No. 38, 205–213 (March 1961).

[5] Woods, D., Admittance standardization and measurement in relation to coaxial systems, IRE Trans. on Instrumentation **I–9**, No. 3, 258–268 (Sept. 1960).

[6] Hersh, J. F., private communication.

[7] Orr, R. and Zorzy, J., More coaxial capacitance standards, General Radio Experimenter **42**, No. 5, 19–23 (May 1968).


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