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A 200-Hz to 30-MHz Computer-Operated Impedance/Admittance Bridge (COZY)

By L. D. WHITE, R. W. COONS, and R. C. STRUM

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For the past few years the development of ferromagnetic components, particularly for long-haul transmission systems, has relied heavily on large numbers of highly accurate impedance measurements made on a computer-operated impedance/admittance bridge (COZY) developed especially for this work. COZY's accuracy and speed enable a level of component development not otherwise possible. COZY automatically measures complex impedance, temperature coefficients of complex impedance, and disaccommodation factors of ferromagnetic materials, providing accuracies of ±0.05 percent for inductance, ±50 microradian for loss angle, and ±10 parts per million for the small impedance changes associated with determinations of temperature coefficients and disaccommodation factors. COZY is easy to use and makes a measurement in 10 to 20 seconds. Also, the calibration of the bridge unit's capacitance and conductance standards can be checked automatically. Though developed primarily for ferromagnetic component work, COZY is a general-purpose bridge; it measures inductance, capacitance, resistance, and conductance over wide impedance ranges at frequencies between 200 Hz and 30 MHz. This paper describes COZY's hardware, software, and performance.

I. INTRODUCTION

A computer-operated impedance/admittance bridge (COZY) has been developed to have the following features:

- wide frequency range—200 Hz to 30 MHz in 0.01-Hz steps
- wide impedance/admittance range—from a resolution of 0.1 nanohenry for small impedances to a resolution of 0.001 picofarad for small admittances
- high accuracy—high-Q unknowns can be measured to ±0.05 percent for inductance/capacitance and ±50 microradians for loss angle. Changes in impedance/admittance (with temperature,

time, shock, and vibration, etc.) can be measured to ±10 parts per million.

- specifiable signal level—voltage or current may be specified over the nominal range of 0.05 to 5 volts for impedances larger than 100 ohms and 0.5 to 50 milliamperes for smaller impedances. The achieved level is within ±10 percent of the requested level and is measured to ±3 percent.
- relatively fast—20 seconds per measurement
- easy to use yet flexible—the bridge has only a single pair of binding posts to which the unknown is connected and the user needs to specify only a test frequency. However, the user can specify signal levels, frequency runs, and various options for post-processing of the measurement results.
- the options for runs and postprocessing can be changed easily—the software clearly separates the options from the basic measurement process.
- automatic aids for maintaining high accuracy—in particular, the calibration of the bridge unit's standards can be automatically checked.

A microcomputer-controlled environmental chamber with an 18-sample capacity is appliqued to COZY. The combined system provides the following additional features:

- Highly accurate automatic measurements of the changes of the samples' impedances/admittances with environmental conditions—temperatures may be specified to ±0.1° Celsius between −40° and 93° Celsius and relative humidities to ±2.5 percent between 20 and 95 percent, with a minimum dew point of 2.5° Celsius. Soak times, signal levels, multiple frequencies, and environmental runs can also be specified. Average time for a single measurement is 10 seconds.
- Automatic meaurements of the disaccommodation factors (the decrease in permeability with time after demagnetization) of ferromagnetic materials—peak demagnetization currents up to 2 amperes, with a 10-volt maximum, can be specified.

COZY was developed to provide the measurements required in ferromagnetic component development work. Large numbers of highly accurate measurements are required to evaluate materials, structures, and whole components over their operating ranges of frequency, signal level, and environmental conditions and to determine the effects of aging, shock, and vibration.

The most crucial of the measurement requirements that led to the development of COZY were: (1) a basic precision of significantly better than ten parts per million to achieve the desired accuracies in measuring high Q-values and small changes in impedance, and (2) a measurement time much less than a minute to provide the desired quantity of measurements. The measuring systems that come closest to meeting these requirements are specially developed manual bridges[1] and the 50-Hz to 250-MHz computer-operated transmission measuring system.[2] The manual bridges have satisfactory precision but require many minutes and much care and expertise for a measurement. The computer-operated transmission measuring system, on the other hand, is amply fast but has a basic precision of approximately 100 parts per million.

To meet the objectives for precision requires bridge techniques; pure transmission measurements are not satisfactory. To achieve short measurement times requires automation, and because the amount and complexity of bridge computations are large, the automation has to be done with a computer.

The development of COZY required new design features and measurement procedures. COZY's bridge differs markedly from manual bridges in two ways. First, small impedances are measured with novel bridge configurations based on techniques previously used to calibrate inductance standards.[1,3] Second, all switching of the bridge configurations and setting of the standards is done by a new design of mercury-wetted contact relay that requires very different design considerations than the wafer switches used in manual bridges.

COZY's measurement process differs significantly from measurement processes in manual bridges in three basic areas: selecting the bridge configuration, balancing the bridge, and obtaining the last 1½ decades of the balance. To determine the bridge configuration for a measurement, COZY calculates an approximate value for the unknown from four transmission-type measurements, three of which use predetermined settings of the bridge to provide a calibration of the system. Balancing is done with an iterative process in which capacitance and conductance standards are changed, the ratio of the change in the admittance of the standards to the change in the bridge output is calculated, and the next change to be made in the standards is calculated by multiplying this ratio by the last bridge output. The final 1½ decades of the balance are determined by measuring the bridge output over a one-second period. If the final degree of balance had been limited by noise, this measurement provides increased resolution by noise averaging. On the other hand, if the degree of balance had been limited by the finite size of the smallest steps of the standards, the measurement provides interpolation between these steps.

To provide information suitable for use in the measurement process, the receiver must be phase sensitive and linear right down to zero signal. This is accomplished by using heterodyne techniques to produce two dc signals whose amplitudes, including signs, represent orthogonal components of the bridge's output signal.[4] The accuracy of the representation is one percent.

To achieve the required control of temperature and humidity, the environmental chamber's heaters, compressor, and humidifer water were put under the control of a microcomputer using specially developed firmware. A microcomputer rather than COZY's computer was used to enable COZY's computer to be free for general purpose measurements while the specified environmental conditions and soak times are being achieved.

This paper describes the hardware, software, and performance of the computer-operated bridge and of the facilities added to the bridge to provide temperature coefficient and disaccommodation factor measurements. Section II describes the bridge unit and other basic hardware. The calibration of the bridge is covered in Section III. Section IV describes the software, including the measurement process, interaction with the user, and postprocessing of the measurement results. Section V gives the measurement accuracy and discusses the sources of measurement uncertainty. Section VI concerns the automatic aids for maintaining the accuracy and hardware. The main features of the hardware and software for automatically measuring the disaccommodation factors of ferromagnetic materials and the effects of temperature and humidity on impedance are described in Section VII. Section VIII is a summary.

II. BRIDGE UNIT AND OTHER BASIC HARDWARE

2.1. General

Figure 1 shows the basic hardware blocks for making impedance measurements: a signal generator, bridge unit, voltmeter connected to the bridge unit, receiver, and analog-to-digital converter, all controlled by a computer through an interface and test panel. Figure 2 is a photograph of COZY when put into service. The two and one-half bay cabinet at the left contains from left to right the signal generator, receiver, and bridge unit. Mounted on the horizontal top surface of the half-bay are the bridge's two binding posts to which the unknown is connected. The six-bay cabinet on the right contains the computer and, at the far end, the interface and test panel. In the middle is a teletypewriter. In the background at the end of the six-bay cabinet is a "step-up" unit that provides computer controlled admittance ballast for automatic calibrations of the bridge's admittance standards.

2.2 Bridge unit

2.2.1 Overall

The bridge is a unity ratio type with 100-ohm resistors forming the ratio arms. Four configurations of the other two arms, accomplished by automatic switching, are used to measure the full-admittance range.

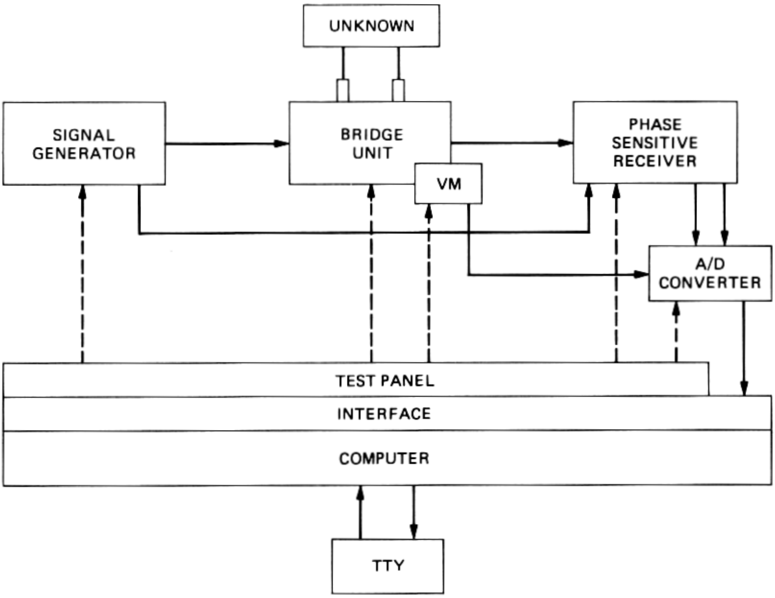


Fig. 1—Block diagram of computer-operated impedance/admittance bridge (COZY).

Figure 3 shows simplified schematics of these configurations. The capacitance standard, C_s, is in the A-D bridge arm for all configurations; the unknown, UNK, may be in either the A-D or the C-D arm; and the conductance standard, G_s, is always in the arm adjacent to the

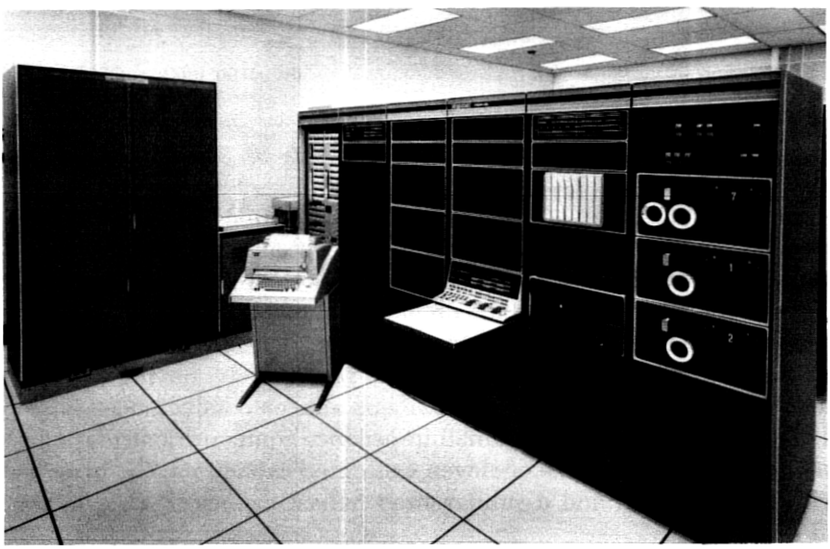


Fig. 2—Computer-operated impedance/admittance bridge (COZY).

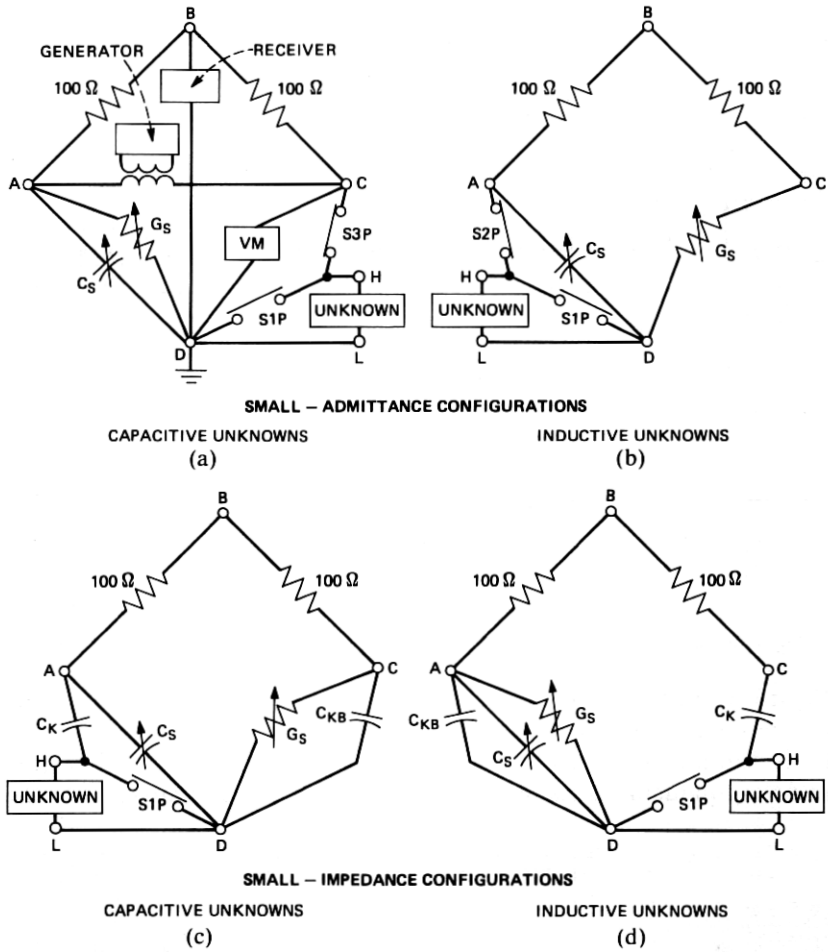


Fig. 3—Bridge configurations.

unknown. The "small-admittance" configuration shown in Fig. 3a is used for capacitive unknowns having susceptances typically smaller than 0.02 siemens and conductances smaller than 0.009 siemens. The Fig. 3b configuration is used for similar-sized inductive unknowns. The "small-impedance" configurations shown in Figs. 3c and 3d are used for capacitive and inductive unknowns, respectively, having susceptances typically larger than 0.02 siemens and/or conductances larger than 0.009 siemens. In these small-impedance configurations measurements are made with one of eleven calibrated capacitors, C_K, in series with the unknown and a similar-sized ballast capacitor, C_{KB}, in the adjacent arm.

As shown in Fig. 3a, signal is applied to the bridge by a transformer connected between the A and C corners; the receiver is connected between the B and D corners; the voltmeter is connected across the C-D arm; and the D corner is grounded.

Each measurement requires manipulating the capacitance and conqductance standards to balance the bridge twice—an unknown balance with the unknown connected into a bridge arm and a reference balance with the unknown effectively out of the arm. The unknown's admittance is computed from the admittance difference between the two balances. For the small-admittance configurations, shown in Figs. 3a and 3b, the unknown balance is made with the switch in series with the unknown closed and the switch shunting the unknown open (as shown). The reference balance is made with the series switch open and the shuntng switch closed. For the small-impedance configurations, shown in Figs. 3c and 3d, the shunting switch is open for the unknown balance and closed for the reference balance.

The bridge's basic blocks and switches are shown in Fig. 4. Two transformers are required to cover the frequency range. One is used from 200 Hz to 101 kHz and the other, from 101 kHz to 30 MHz. Both are double-shielded and specially developed for bridge use. The transformers' intershield capacitances, 90 pF and 15 pF, are large enough to require the complete disconnection of the unused transformer.

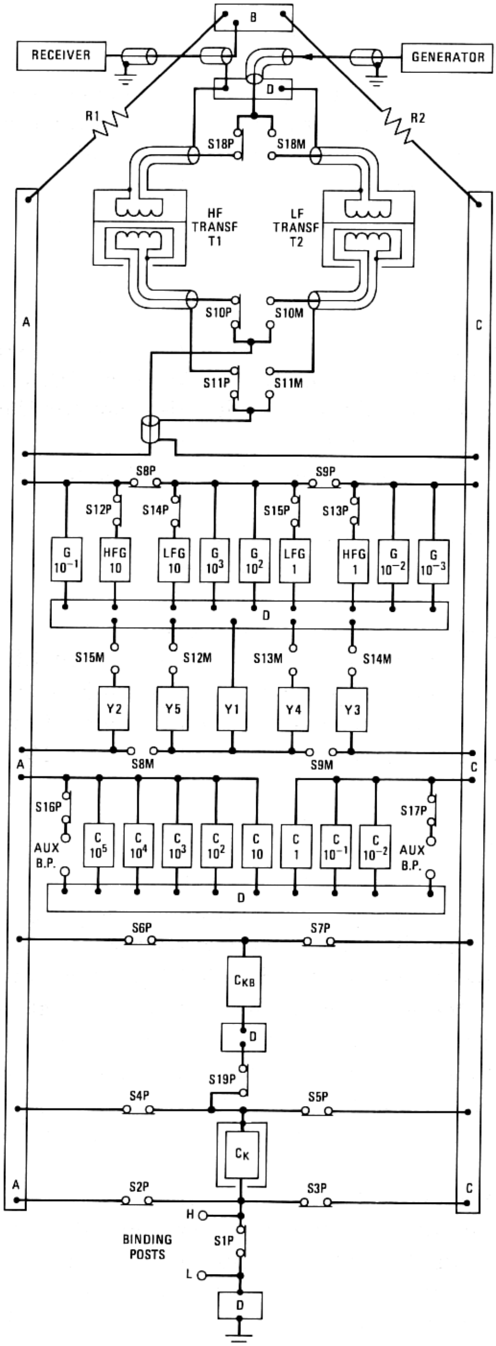
The ratio arm resistors, R_1 and R_2, are 0.01-percent metal film resistors having very small parasitic impedances so that their resistances are frequency independent well beyond the requirements of this bridge. The time constant of the ratio was adjusted to be within 10 ps of zero.

The capacitance standard consists of eight decades covering 1.1 μF in 0.01-pF steps. The 1-, 0.1-, and 0.01-pF per step decades are wired into the C-D bridge arm. Since the capacitance standard is treated as being in the A-D arm, these decades are operated in reverse; that is, their "zero" settings are their maximum capacitance settings.

The conductance standard covers 11,000 μS in 0.001-μS steps and consists of nine decades; low frequency and high frequency versions of the 1- and 10-μS per step decades are necessary to cover the frequency range. The 1000-, and 100-μS and the low frequency 10- and 1-μS per step decades can be switched into either the A-D or C-D arm. The remaining conductance decades are wired into either the A-D or C-D arm.

The distribution of decades among the A-D arm, the C-D arm, and being switched was based on considerations of simultaneously minimizing the total admittance in the arms, the number of leads at a bridge corner, and the frequency dependencies of the decades.

The switched admittances Y_1 through Y_5 compensate for the changes in admittances in the A-D and C-D arms that accompany switching the conductance decades from one arm to the other. For



RESISTORS

R1, R2 – 100 OHM

TRANSFORMERS

T1 – USED 101 kHz TO 30 MHz
T2 – USED 200 Hz TO 101 kHz

CONDUCTANCE STANDARD (9 DECADES)

G 10^{-3} – 0.001 μS/STEP
G 10^{-2} – 0.01 μS/STEP
G 10^{-1} – 0.1 μS/STEP
LFG 1 – 1 μS/STEP (200 Hz – 5 MHz)
HFG 1 – 1 μS/STEP (5 MHz – 30 MHz)
LFG 10 – 10 μS/STEP (200 Hz – 15 MHz)
HFG 10 – 10 μS/STEP (15 MHz – 30 MHz)
G 10^{2} – 100 μS/STEP
G 10^{3} – 1000 μS/STEP

CAPACITANCE STANDARD (8 DECADES)

C 10^{-2} – 0.01 pF/STEP
C 10^{-1} – 0.1 pF/STEP
C 1 – 1 pF/STEP
C 10 – 10 pF/STEP
C 10^{2} – 100 pF/STEP
C 10^{3} – 0.001 μF/STEP
C 10^{4} – 0.01 μF/STEP
C 10^{5} – 0.1 μF/STEP

CONDUCTANCE STANDARD COMPENSATORS

Y1 – COMPENSATES FOR THE RESIDUAL ADMITTANCE OF THE G 10^2 AND THE G 10^3 DECADES. WHEN THE DECADES ARE IN THE A-D ARM, Y1 IS IN THE C-D ARM; AND VICE VERSA.

Y2 – COMPENSATES FOR THE RESIDUAL ADMITTANCE OF THE HFG 1 DECADE. WHEN HFG 1 IS BEING USED, IT IS IN THE C-D ARM AND Y2 IS IN THE A-D ARM.

Y3 – COMPENSATES FOR THE RESIDUAL ADMITTANCE OF THE HFG 10 DECADE. WHEN HFG 10 IS BEING USED, IT IS IN THE A-D ARM AND Y3 IS IN THE C-D ARM.

Y4 – COMPENSATES FOR THE RESIDUAL ADMITTANCE OF THE LFG 1 DECADE. WHEN LFG 1 IS BEING USED, IT IS IN THE ARM CONTAINING G 10^3 AND Y4 IS IN THE ARM CONTAINING Y1.

Y5 – COMPENSATES FOR THE RESIDUAL ADMITTANCE OF THE LFG 10 DECADE. WHEN LFG 10 IS BEING USED, IT IS IN THE ARM CONTAINING G 10^3 AND Y5 IS IN THE ARM CONTAINING Y1.

SERIES CAPACITANCE STANDARD

C_K CONSISTS OF ELEVEN CALIBRATED CAPACITANCE SETTINGS. THEIR NOMINAL VALUES ARE 10 pF, 30 pF, 100 pF, 300 pF, 1 nF, 3 nF, 10 nF, 30 nF, 100 nF, 300 nF and 1.1 μF. C_K IS CONNECTED IN SERIES WITH THE UNKNOWN WHEN THE UNKNOWN'S ADMITTANCE IS TOO LARGE TO BE MEASURED BY COMPARISON WITH THE CONDUCTANCE AND CAPACITANCE STANDARDS.

SERIES CAPACITANCE BALLAST

C_{KB} CONSISTS OF ELEVEN CAPACITANCE SETTINGS HAVING THE SAME NOMINAL VALUES AS C_K. WHEN C_K IS IN THE A-D ARM, C_{KB} IS IN THE C-D ARM; AND VICE VERSA. C_K AND C_{KB} ARE SET TO THE SAME NOMINAL VALUE AND THE CAPACITANCES OF C_{KB} HAVE BEEN ADJUSTED SO THAT WHEN SWITCH S1P IS CLOSED, THE BRIDGE BALANCES AT LOW SETTINGS OF THE CONDUCTANCE AND CAPACITANCE STANDARDS.

MODE SWITCHES

S1 THROUGH S19 ARE SPECIAL MERCURY-WETTED CONTACT RELAYS WITH TWO MAGNETIC POLES LABELED M AND TWO PLATINUM POLES LABELED P. WITH POWER APPLIED TO A RELAY'S COIL THE MAGNETIC POLES ARE BRIDGED WITH A SHORT CIRCUIT. WITHOUT POWER THE PLATINUM POLES ARE BRIDGED.

D-CORNER

THE FIVE D-SECTIONS REPRESENT THE SINGLE D-CORNER.

Fig. 4—Schematic diagram of bridge unit.

example, Y_1 compensates for the capacitance changes associated with switching the 1000- and 100-μS decades. When the decades are in the A-D arm, Y_1 is in the C-D arm, and vice versa.

The calibrated series capacitor, C_K, and the ballast capacitor, C_{KB}, used in the small-impedance configurations, may be set to: 10, 30, 100, 300, 1000, 3000 pF and 0.01, 0.03, 0.1, 0.3, and 1 μF. The series capacitor, C_K, is contained within a shield and the shield and capacitor can be connected to the A, C, or D corner. The ballast capacitors were adjusted during prove-in so that the bridge balances with low settings on the capacitance and conductance standards when the switch, S1P, across the binding posts is closed.

The bridge was mechanically designed with the following objectives in mind: as low as possible impedances in series with the various components; the components in one arm shielded from the components in the other arms; and the basic blocks in each arm to have independent leads to the junction points with the adjacent arms and the associated generator or receiver connection, thus well defining each bridge corner. The ratio resistors and the A, B, C, and D corner blocks are contained in a central rigid structure. The capacitance and conductance decades are connected to the A or C block and the D block with coaxial cables.

All the circuit components were selected for stability with time, temperature, humidity, and vibration. In addition, the bridge temperature is held constant to better than ±0.05° Celsius.

A critical circuit component, developed specially for this bridge, is the relay used for all switching. The relay contains a mercury-wetted contact switch, shown in Fig. 5, with the leads to the normally open contacts made of magnetic alloy and the leads to the normally closed contacts made of platinum. With no power applied to the relay the two platinum leads are shorted by a bar carried by the armature. When power is applied, this bar moves to short the two magnetic alloy leads. The magnetic alloy leads provide part of the magnetic circuit that permits the relay to be operated without external magnets, which would be too bulky. The platinum leads give a stable low-impedance path for the critical circuits; the alloy leads' resistance changes so much with time after a relay is switched, due to temperature changes caused by local heating, that these leads can be used only in very high impedance or noncritical circuits. A specially designed shield and coil assembly electrostatically shields the capsule from its driving coil and surrounds the whole assembly with an electromagnetic shield that completes the magnetic circuit.

The switch is very stable and reproducible. Measurements with manual bridges showed that the switches reset with variations of less than ten micro-ohms in series resistance and one thousandth picofarad in shunt capacitance.

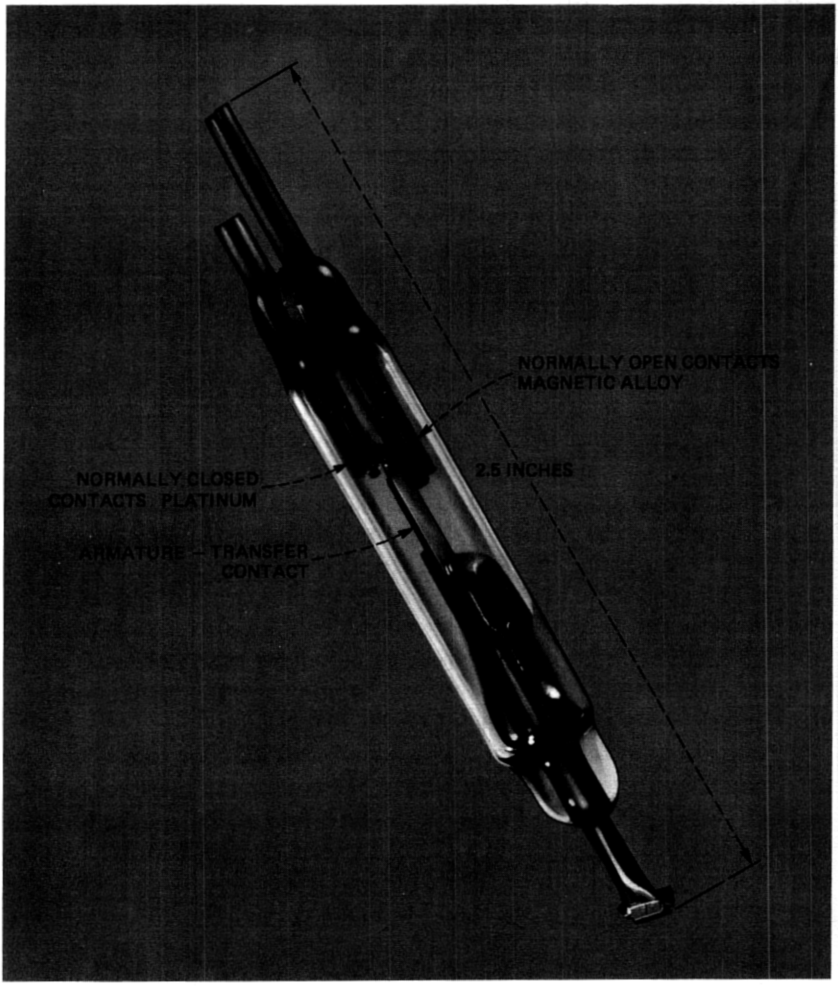


Fig. 5—Special mercury-wetted contact switch used in the bridge unit's relays.

However, the switch has some disadvantages. It must be used upright; it is relatively large with a horizontal center-to-center spacing of three-quarters of an inch; and it has 5-pF capacitance from the armature to the grounded shield.

Figure 6 is a photograph looking down on the bridge. So that the details show, the top cover and the cover of the shield surrounding the ratio resistors have been removed. The junction of the detector lead with this shield is the B corner. The A and C corners are below the high binding post, *H*, which is shown. The D corner is below the A and C corners. The low binding post, *L*, is mounted on the top cover and in use is located above the shield around the ratio resistors.

2.2.2 *Design of admittance standards and series capacitor*

A fundamental objective in designing the capacitance and conductance standards was to achieve wide frequency performance. The problem is that the admittances of the steps of the decades typically increase with increasing frequency and the percentage increases are larger for the larger steps. As a result, at high frequencies gaps occur in the admittances that can be provided by the standards.

Accommodation for some increases in the admittances of the decades' steps is achieved by using decades that employ 11 settings: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10. The ten-settings provide overlaps at low frequencies in the admittance ranges obtained with successive settings of any decade except the least significant one. For example, at low frequencies the maximum capacitance that can be obtained with the one-setting of the 100-pF per step decade being the most significant setting is 211.10 pF. This capacitance is obtained by setting the 100-pF through 0.01-pF per step decades to 1-10-10.-10-10, respectively. On the other hand, the minimum capacitance obtainable with the two-setting of the 100-pF decade is 200 pF, achieved with decade settings of 2-0-0.-0-0. Thus, there is an 11.1-pF overlap in the capacitance

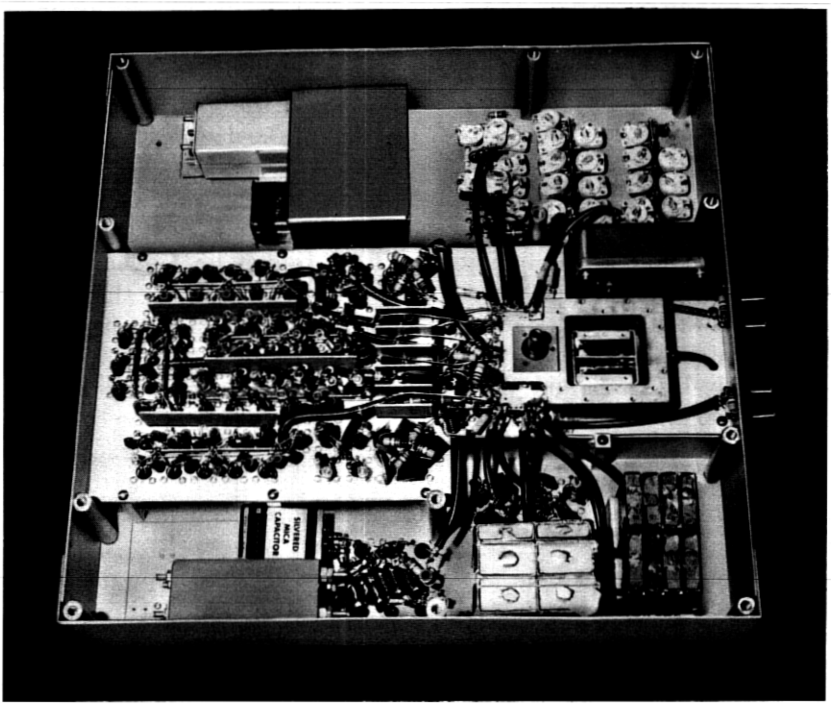


Fig. 6—Top view of bridge unit.

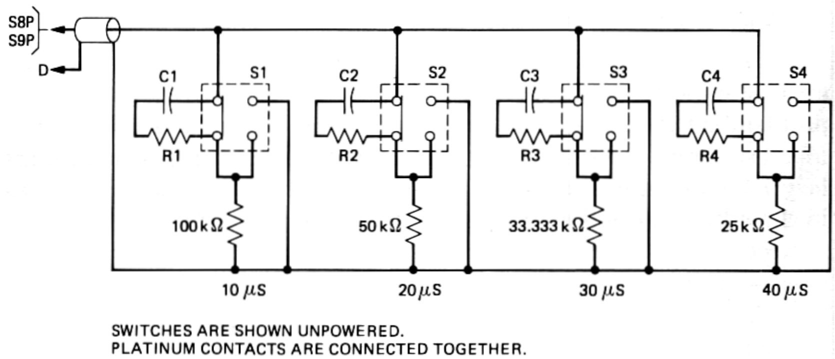


Fig. 7—Schematic diagram of low-frequency 10-microsiemens per step decade.

ranges provided by the one- and two-settings of the 100-pF decade. Consequently, the capacitance of the two-setting can increase to being 111.1 pF larger than that of the one-setting before a gap develops between their associated capacitance ranges.

Two general types of decades are used in the COZY bridge: an "adding" type consisting of four units that singly and in combination form a complete decade, and a "residual" type consisting of 10 or 11 capacitors (or resistors) switched singly into series with a common much smaller capacitor (or larger resistor). The 100,000-pF, 10,000-pF, 1000-pF, 100-pF, 10-pF, 1000-μS, 100-μS, and the low frequency 10- and 1-μS decades are adding type. The rest of the decades are residual type.

The most complex of the adding type decades is the low-frequency 10-μS per step decade, which is used up to 15 MHz. Figure 7 shows the decade. The individual units are 10, 20, 30, and 40 μS. Capacitors are used to compensate for the 5-pF capacitances between the switch armatures and ground, thereby making the decade's capacitance independent of switch settings. The resistors in series with the capacitors are relatively small and were selected to yield conductances that partially compensate for the increases with frequency of the conductances of the unit resistors as a result of their distributed capacitances. Thus, the admittance differences between the decade's settings are almost pure conductance and as independent of frequency as is practical.

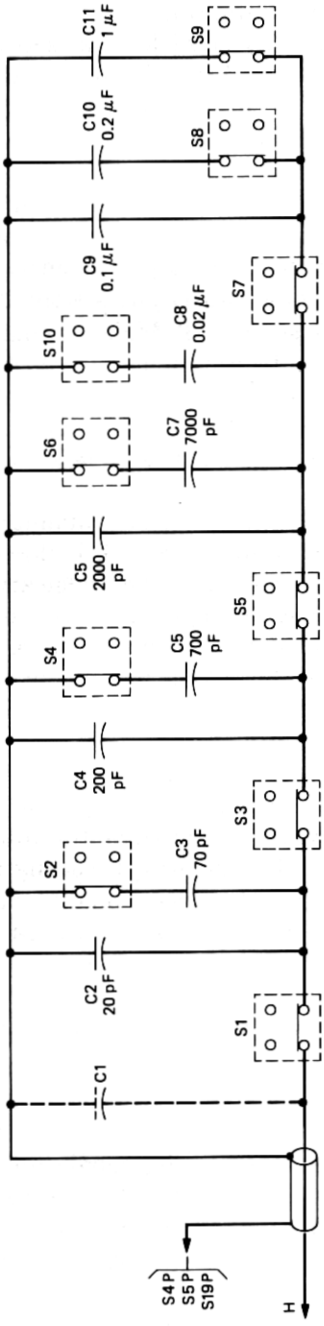
However, at frequencies above 15 MHz a residual type decade is needed to achieve 10-μS steps. The decade contains 11 resistors, ranging from 100 to 404.76 ohms, that can be switched singly into series with a 1500-ohm resistor. Across each resistor is a capacitor adjusted to achieve the same time constant for each resistor and thereby to make the conductance differences between the settings independent of frequency. This decade is not used at low frequencies because it adds 525 μS to the bridge's residual admittance.

As with the bridge standards, a design objective for the series capacitors, C_K, was to minimize the increases in their effective capacitances with increasing frequency. However, because the switches have 5-pF capacitance from armature to ground and 0.7 pF across an open switch, a more difficult objective was to achieve at the smaller settings satisfactorily small values for the capacitances in series with and shunting the binding posts. If these capacitances are too large, gaps will exist in the bridge's impedance coverage at the top frequencies. For example, if the minimum values for these capacitances were 12 pF, then a 1-μH unknown could not be measured at 30 MHz—it could not be measured with a small admittance configuration because its 36-pF resonating capacitance exceeds the capacitance standard's 30-pF range and it could not be measured with a small-impedance configuration because the difference between the unknown and reference balances would be 37 pF.

Figure 8 shows the design of the series capacitor, C_K. The minimum setting is with switch S1 open and switch S2 closed. Switch S2 is closed to put slightly more of the parasitic capacitance across the bridge arm where it is harmless. For this setting, the series capacitance is composed entirely of the capacitance of the wiring to the shield and amounts to 10 pF. The capacitance shunting the unknown is also about 10 pF. These capacitances are small enough to provide continuous impedance coverage between the small-admittance and small-impedance configurations. The 30-pF setting of the series capacitor is obtained by closing switch S1 only, which adds a 20-pF capacitor. The 5-pF armature-to-ground capacitance of switch S1 increases the total capacitance shunting the unknown to 15 pF. The 100-pF setting is obtained by closing switches S1, S2, and S4. However, no additonal capacitance is thrown across the unknown since the armature-to-ground capacitance of switch S2 is across the bridge arm. Switch S4 is closed only to concentrate the remaining parasitic capacitances across the whole bridge arm. This type of switching is continued through the higher values of C_K.

2.3 Other basic hardware

The generator contains a frequency synthesizer as the signal source and can supply between 1 millivolt and 10 volts in 0.05-dB steps to a 75-ohm load. The criteria used in selecting the synthesizer included low phase noise and low harmonics, and in selecting amplifiers, high linearity. These criteria are important because many bridge balances are narrow band. In these balances phase noise contributes to the noise at balance and so must be kept low. Also, harmonics are not



SWITCHES ARE SHOWN UNPOWERED.
PLATINUM CONTACTS ARE CONNECTED.

C2 THROUGH C10 WERE ADJUSTED SO THAT THE SERIES CAPACITORS WERE WITHIN ONE PERCENT OF NOMINAL.

NOMINAL VALUE OF SERIES CAPACITOR	CLOSED SWITCHES (CLOSED SWITCHES ARE NOT POWERED)
10 pF	S2
30 pF	S1
100 pF	S1, S2, S4
300 pF	S1, S2, S3
1,000 pF	S1, S2, S3, S4
3,000 pF	S1, S2, S3, S4, S5
0.01 μF	S1, S2, S3, S4, S5, S6
0.03 μF	S1, S2, S3, S4, S5, S6, S10
0.1 μF	S1, S3, S5, S7
0.3 μF	S1, S3, S5, S7, S8
1.1 μF	S1, S3, S5, S7, S9

Fig. 8—Schematic diagram of the series capacitor, C_K.

strongly attenuated and thus care must be taken to prevent them from intermodulating in the receiver to produce a false fundamental. Harmonics in the generator's output are more than 30 dB down from the fundamental.

The receiver's minimum detectable signal is no larger than 0.05 microvolts (with a one-second measurement time) and the receiver is linear for input signals up to at least 5 volts. Maximum voltage gain is one million and at full gain intermodulation of 0.16-volt second and third harmonics (corresponding to 30 dB down from a 5-volt fundamental) produces less than two microvolts of fundamental referred to the input. Crosstalk corresponds to less than 0.05 microvolts of fundamental at the input. Settling times and overload recovery times are no more than 1 ms except for input frequencies below 4.9 kHz, where the settling time is 17 ms.

Between 120 kHz and 30 MHz, two stages of frequency translation are used. The first stage uses a synthesizer as a local oscillator and produces an IF signal at 28 kHz. The second stage uses two ring modulators in parallel to translate the IF signal to two dc voltages. The local oscillator sources for the modulators are two 28-kHz sine waves, with a 90 degree phase difference between them, generated from the same signal sources used to generate the IF signal.

Between 200 Hz and 120 kHz, three stages of frequency translation are used: from 200 Hz to 4.9 kHz, the 28-kHz IF is preceded by a 97-kHz IF; and from 4.9 kHz to 120 kHz, by a 528-kHz IF.

A low-pass filter preceding the first mixer attenuates harmonics of the test frequency so that they do not generate significant IF signals by intermodulation in the mixer. The receiver contains 29 of these low-pass filters and each filter is used over a frequency range of approximately two-thirds of an octave, i.e., the filters cover 200 to 315 Hz, 315 to 480 Hz, etc. The filters below 45 kHz are active and have input impedances of 600 ± 2 ohms. The filters above 45 kHz are passive and have 75-ohm input impedances and return losses larger than 15 dB.

The receiver's two dc outputs are read one after the other into the computer by the A/D converter. Noise averaging is done by taking successive pairs of readings with 1.4 ms between each pair. The A/D converter covers the range from −10 Vdc to +10 Vdc with a 15-bit (including sign) output. At the converter's input is a 48-channel multiplexer.

A specially developed voltmeter is connected across one arm of the bridge and puts out a dc voltage proportional to the rf voltage at its input. Four gain settings are used to cover the 0.05- to 5-volt range and the ratios of the dc to rf voltages are within two percent of the nominal values. One percent accuracy is achieved with simple computer corrections. Voltages below 0.05 volts can be measured with some degradation in accuracy. The response time for one percent accuracy is 24 ms. An important feature of the voltmeter is that its input admittance is very stable and small; it is 7.2 pF and 0.4 μS at 100 kHz.

The test panel contains a light for observing and a switch for manually controlling the state of each computer-controlled relay. Manual control of the relays is valuable for prove-in and trouble diagnosis of the system. Observation of the lights during the measurement process yields information on whether the process is going well, and if not, where the source of trouble is.

The computer originally included automatic priority interrupt, 24K words of core memory, a 256K-word fixed head disk and three magnetic tape drives. Since then the computer has been upgraded to include 32K words of core memory, two 1¼ M-word cartridge disks, and floating-point hardware.

III. CALIBRATION OF THE BRIDGE UNIT

3.1 General

Calibration values are determined for the capacitance and conductance of each step of the capacitance standard, the conductance standard, and the series capacitors and of the various admittances that appear in the equivalent circuits used in data reduction. These determinations are made at the 18 frequencies of 0.2, 0.5, 1, 2 kHz, $\cdots$, 2, 5, 10, 15, 20, and 30 mHz.

The equivalent circuits for data reduction are given in Section 3.2 and the basic calibration procedures are given in Sections 3.3 and 3.4. However, note that in some cases the actual calibration values assigned are based on more than a single method of determination.

3.2 Equivalent circuits for data reduction

Data reduction is based on simplified equivalent circuits relating an unknown's admittance to the admittance difference between the unknown and reference balances. An objective in choosing the equivalent circuits was that their various admittances could be evaluated with relatively simple procedures and available external admittance standards.

Figure 9 shows the equivalent circuits used for the unknown and reference balances for the small-admittance configuration when measuring capacitive unknowns. Only three admittances per balance are necessary to characterize the circuitry connecting the unknown to the bridge corners. These equivalent admittances may, of course, be strongly frequency dependent. In the reference balance, the impedance of the short-circuiting switch across the binding posts is so small compared to the impedance in series with it and the impedance of the unknown that the unknown's impedance does not significantly affect the reference balance. Thus, the three equivalent admittances for the reference balance reduce to one.

From Fig. 9, the admittance difference, $Y_U - Y_R$, between the unknown and reference balances is given by

$$Y_U - Y_R = \frac{Y_X + Y_{HD}}{1 + Z_{CH}(Y_X + Y_{HD})} + Y_{CD} - Y_{CR}, \tag{1}$$

where Y_X is the admittance of the unknown. As part of the calibration procedure, the admittance difference, Y_{UR}, between unknown and reference balances with nothing across the binding posts, is measured

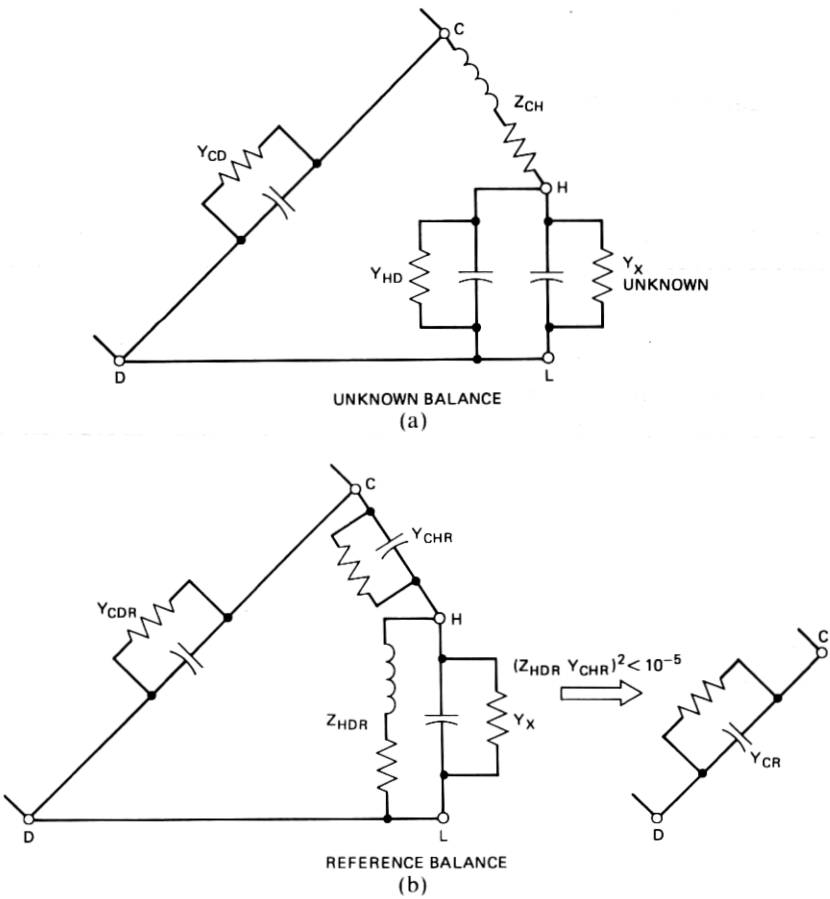


Fig. 9—Equivalent circuits used for reducing measurement data taken with the small-admittance configuration of Fig. 3a.

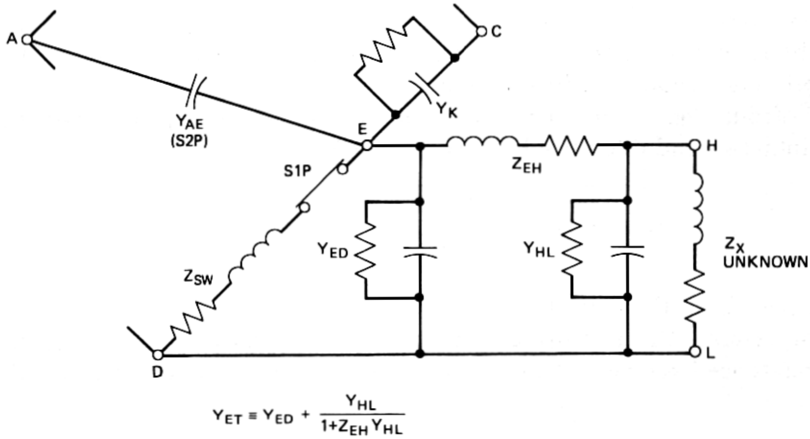


Fig. 10—Equivalent circuit used for reducing measurement data taken with the small-impedance configuration of Fig. 3d.

and stored. This difference is given by

$$Y_{UR} = \frac{Y_{HD}}{1 + Z_{CH}\, Y_{HD}} + Y_{CD} - Y_{CR}. \tag{2}$$

Substituting the expression for $Y_{CD} - Y_{CR}$, obtained from eq. (2) into eq. (1), yields

$$Y_U - Y_R = \frac{Y_X}{[1 + Z_{CH}(Y_X + Y_{HD})]\cdot[1 + Z_{CH}\, Y_{HD}]} + Y_{UR}. \tag{3}$$

This equation is the basis for data reduction. Values for Y_{HD} and Z_{CH} are determined and stored in files as part of the calibration process.

For unknowns having small inductive admittances the values for the equivalent circuit admittances are for the A-D arm.

Figure 10 shows the equivalent circuit for data reduction of inductive unknowns measured with the small-impedance configuration. The unknown balance is made with the short-circuiting switch, S1P, open; and the reference balance, with the switch closed. Y_K is the effective admittance between the C corner and the E junction. Y_{AE} is the admittance across the open switch, S2P (see Fig. 4), to the A corner and is about 0.7 pF. The admittance difference, $Y_U - Y_R$, between the settings of the standards for the unknown and reference balances is

$$Y_U - Y_R = \frac{-(Y_K^2 - Y_{AE}^2)}{[1 + Z_{SW}(Y_K + Y_{AE} + Y_{XE})](Y_K + Y_{AE} + Y_{XE})}, \tag{4}$$

where

$$Y_{XE} = Y_{ED} + \frac{Y_X + Y_{HL}}{1 + Z_{EH}(Y_X + Y_{HL})}. \tag{5}$$

The equivalent circuit for measuring small impedance capacitive unknowns differs from Fig. 10 only in that the unknown is connected into the A-D arm.

3.3 Calibration of the bridge standards and of the parasitic admittances for the small-admittance configurations

Determining the calibrations for the capacitance and conductance standards involved four very different phases: (1) the individual steps of the standards were intercompared and consistent calibrations for the standards were obtained by a step-up calibration[5,6]; (2) the magnitude and phase of the bridge ratio were determined; (3) the admittance, Y_{HD}, shunting the binding posts in the small-admittance configuration for measuring capacitors was evaluated; and (4) the impedance, Z_{CH}, in series with the binding posts and absolute values for the capacitance and conductance standards were determined from measurements of external standards.

In a step-up calibration, each incremental step of each decade is compared with the full range of the next smaller decade. For example, consider the calibration of the steps of the 10-pF per step decade. The bridge is set in the configuration for measuring small capacitance, Fig. 4a, and external adjustable capacitance and conductance ballast is connected to the bridge's binding posts. The capacitance standard's 10-pF through 0.01-pF decades are set to 0-10.-5-5; the conductance standard is set to 0-0-5-5.-5-5-5; and the bridge is balanced by adjusting the external ballast. Then the 10-pF decade is set to one, the 1-pF decade is set to zero, and the bridge is rebalanced using the 0.1-pF decade, the 0.01-pF decade, and the conductance standard. Assume the standards' settings at this second balance are 1-0.-5-2 pF and 0-0-5-5.-5-1-2 μS. From the bridge settings we would calculate that the first step of the 10-pF decade is 0.03 pF and 0.043 μS larger than the full 10-pF range of the 1-pF decade. Similarly, the size of the step between the one- and two-settings of the 10-pF decade is then compared with the full range of the 1-pF decade by making balances with these decades set first at 1-10 and then at 2-0. The steps of the 1-pF decade are in turn compared with the full range of the 0.1-pF decade and the steps of that decade, with the 0.01-pF decade.

The 0.01-pF decade cannot be compared with a smaller decade—there is none. Instead, the individual incremental steps of the decade are intercompared via transmission-type measurements made with the receiver, and the results are processed to yield a calibration for the one- through ten-settings relative to the full range of the decade.

After all the steps of all the decades have been intercompared, the data is processed to yield a consistent calibration. The processing starts at the smallest decades and proceeds up both the capacitance and conductance decades. The calibration calculated for the conductance decades is applied in reducing the data for the capacitance decades and vice versa.

The step-up calibration for the capacitance standard differs from the absolute calibration in magnitude and phase angle, the same percentage difference and the same phase angle difference for each setting of each decade. Thus, the capacitance and conductance corrections to be added to the step-up calibrations for the individual steps are proportional to the capacitances of the steps. Similarly for the conductance standard, the differences between its step-up calibration and its absolute calibration are a percentage for the conductance of each step and a capacitance proportional to the step's conductance for the capacitance of each step.

The magnitude and phase angle of the bridge ratio were determined using the auxiliary binding posts symmetrically connected across the A-D and C-D bridge arms via mode switches S16P and S17P (see Fig. 4). Bridge balances were made with: (1) nothing across the auxiliary binding posts; (2) a capacitance C_A connected to the A-D binding posts, and a similar sized capacitance C_C connected to the C-D binding posts; and (3) C_C connected to the A-D binding posts and C_A to the C-D binding posts. The effects of any differences between the series impedances of the internal coaxial leads between the bridge corners and the auxiliary binding posts were calculated and taken into account by making similar balances using a different capacitance value for C_A and C_C.

The admittance, Y_{HD}, shunting the binding posts in the small-admittance configuration was measured by using switches S3P and S2P to connect Y_{HD} first into the C-D arm and then into the A-D arm. Y_{HD} is one-half the difference between the two resulting balances, corrected for the effects of the impedances in series with Y_{HD} and of the armature-to-ground capacitances in switches S2P and S3P.

The impedance, Z_{CH}, in series with the binding posts was determined and absolute calibrations for the bridge standards were obtained by measuring external standards. Two external capacitance standards were measured in terms of the step-up calibration. The data-reduction equations with known values for the unknowns and the admittance Y_{HD} were then solved for the value for the series impedance Z_{CH} and the percentage and phase-angle corrections to be made in the step-up calibration for the bridge's capacitance standard. Then, an external conductance standard was measured to determine the percentage and phase angle corrections to be made in the step-up calibration of the bridge's conductance standard.

The external capacitance standards used at frequencies up to 100 kHz were mica capacitors calibrated on a Type 12 capacitance bridge[7] that has a basic accuracy of ±50 ppm for capacitance and ±25 microradians for loss angle. At frequencies above 100 kHz, the external capacitance standards were parallel plate capacitors with air dielectric and geometries permitting their conductances and the frequency dependencies of their capacitances to be calculated. The low-frequency capacitances of these standards were obtained by measuring them on the bridge at 100 kHz using the calibration obtained with the external mica capacitance standards. The parallel plate capacitors were not disturbed between the 100-kHz measurements and the higher-frequency measurements.

The external conductance standards were 100- and 1000-ohm metal film resistors whose conductances and shunt capacitances were determined by various procedures using the Type 12 capacitance bridge and a Wheatstone bridge having a basic accuracy of ±10 parts per million. The conductances and capacitances of these resistors are not significant functions of frequency.

The impedance in series with the binding posts when they are connected into the A-D arm was evaluated by comparing measurements made in the A-D arm with measurements made in the C-D arm. Also, the admittance difference between the unknown and reference balances with nothing connected to the binding posts was measured with the binding posts in the A-D arm.

Step-up calibrations of the standards, including the intercomparisons of the steps and the data reduction, are done automatically at frequencies up to 5 MHz. For these calibrations the adjustable capacitance and conductance ballast connected to the bridge's binding posts is a specially developed "step-up unit" under computer control. This unit contains capacitance and conductance decades similar to those in the bridge. The steps of the step-up unit's decades are calibrated by automatically measuring them with the bridge.

Above 5 MHz the performance of the step-up unit is unsatisfactory and special manually adjustable capacitance and conductance ballasts are used. The intercomparison process is semiautomatic, with the operator adjusting the ballast and the computer balancing the bridge, recording the results, and reducing the data.

Measurements of the admittance differences between the unknown and reference balances with nothing connected to the bridge's binding posts are also done automatically.

3.4 Calibration of the series capacitors and parasitic admittances for the small-impedance configurations

The admittances/impedances in the equivalent circuit of Fig. 10 for the small-impedance configurations were evaluated in four phases.

The direct capacitance, C_{AE}, from the E junction to the A corner via the open switch S2P was measured at 10 kHz with the Type 12 capacitance bridge.

The admittances, Y_K and Y_{ET}, in series with and shunting the unknown were determined from various bridge balances. For example, at the setting for minimum series capacitance three balances were made: one with the two admittances in series and one each with the individual admittances connected across the C-D arm. Corrections for the shunt admittances and series impedances of the switches used to connect in the individual admittances enter into the determinations.

The admittance, Y_{HL}, across the binding posts was estimated to be 2 pF.

The switch impedance, Z_{SW}, and the binding post impedance, Z_{EH}, were determined from measurements of the impedance differences between the individual impedances and the impedances in parallel. Three bridge balances were made using the small-impedance configuration and the largest series capacitor calibrated at the frequency of the determination. One balance was with the switch, S1P, closed and nothing across the binding posts. Another balance was with the switch open and the binding posts short-circuited by a metallic plate having effectively zero impedance. The third balance was with the switch closed and the binding posts short-circuited.

The bridge construction is so symmetrical that the values for the circuit elements for the unknown in the A-D arm are the same as for the unknown in the C-D arm.

The measurements and data reduction are done automatically for the series and shunt admittances, Y_K and Y_{ET}, and for the switch and binding post impedances, Z_{SW} and Z_{EH}.

IV. SOFTWARE AND MEASUREMENT PROCESS

4.1 Software structure

The structure of the software for making measurements embodies a clearly defined division of responsibility between the measurement function and the user interaction and post processing functions. This enables the measurement center personnel responsible for the day-to-day operation to respond to changing customer needs without getting involved in the measuring process itself.

Three modules, labeled INPUT, OUTPUT, and CNTROL, provide for the user interaction and post processing. They were written by the measurement center. One module, MEASUR, provides the measurement process and was written by the developers of COZY. The INPUT module conducts the dialogue with the user. When the dialogue is completed, INPUT passes the collected data and program control to the CNTROL module. CNTROL oversees the making of measurements according to the user-supplied data. For each individual measurement, i.e., a single unknown at a single frequency and a single signal level, CNTROL passes the measurement frequency and signal level to MEASUR. MEASUR then makes the measurement. When all the specified measurements have been made, CNTROL passes the data and program control to the OUTPUT module. OUTPUT processes the measurement results according to the user requests specified to INPUT and presents the processed data in the desired formats.

The INPUT, CNTROL, and OUTPUT modules are each separate overlays. Part of MEASUR is in the CNTROL overlay but the bulk of MEASUR is in two additional overlays.

4.2 MEASUR—The measurement module

The module MEASUR contains all the routines required to measure one unknown at one frequency and one signal level. The test frequency and the desired signal level are passed to MEASUR via dedicated locations in the COMMON storage area. Similarly, MEASUR fills other dedicated locations in COMMON with the measurement results. Included in these results are: the unknown's admittance as seen at the bridge binding posts, the measured signal level applied to the unknown, and information specifying the bridge configuration used.

Figure 11 shows a flowchart for MEASUR. MEASUR starts by tuning the generator and receiver for the specified test frequency and setting the signal level and the receiver gain to their minimum values. Then the calibration data for the capacitance standard, the conductance standard, the series capacitors, and the bridge's parasitic admittances are obtained. For measurement frequencies that correspond to calibration frequencies, the data is read from disk files. For measurement frequencies between the calibration frequencies, admittance values are obtained by interpolation between the values at the calibration frequencies next above and below the measurement frequency. The interpolation formulas are based on the physical causes for the frequency dependencies. The formulas were checked by comparing calibration values at a calibration frequency with values obtained by interpolation using the next lower and higher calibration frequencies.

To efficiently select a bridge configuration and start the balancing process, an approximate value for the unknown's admittance is determined. Preparatory to determining the approximate value, the signal level is set so that during the determination the level applied to the unknown will not exceed that specified for the actual measurement. This level is set by effectively placing the voltmeter across the A-C bridge diagonal, i.e., across the secondary of the transformer, and adjusting the generator to the voltage requested by the user. For this preliminary level setting, a specified current is expressed as the corresponding voltage across a 100-ohm resistance, which is approximately the impedance in series with the unknown during the determination.

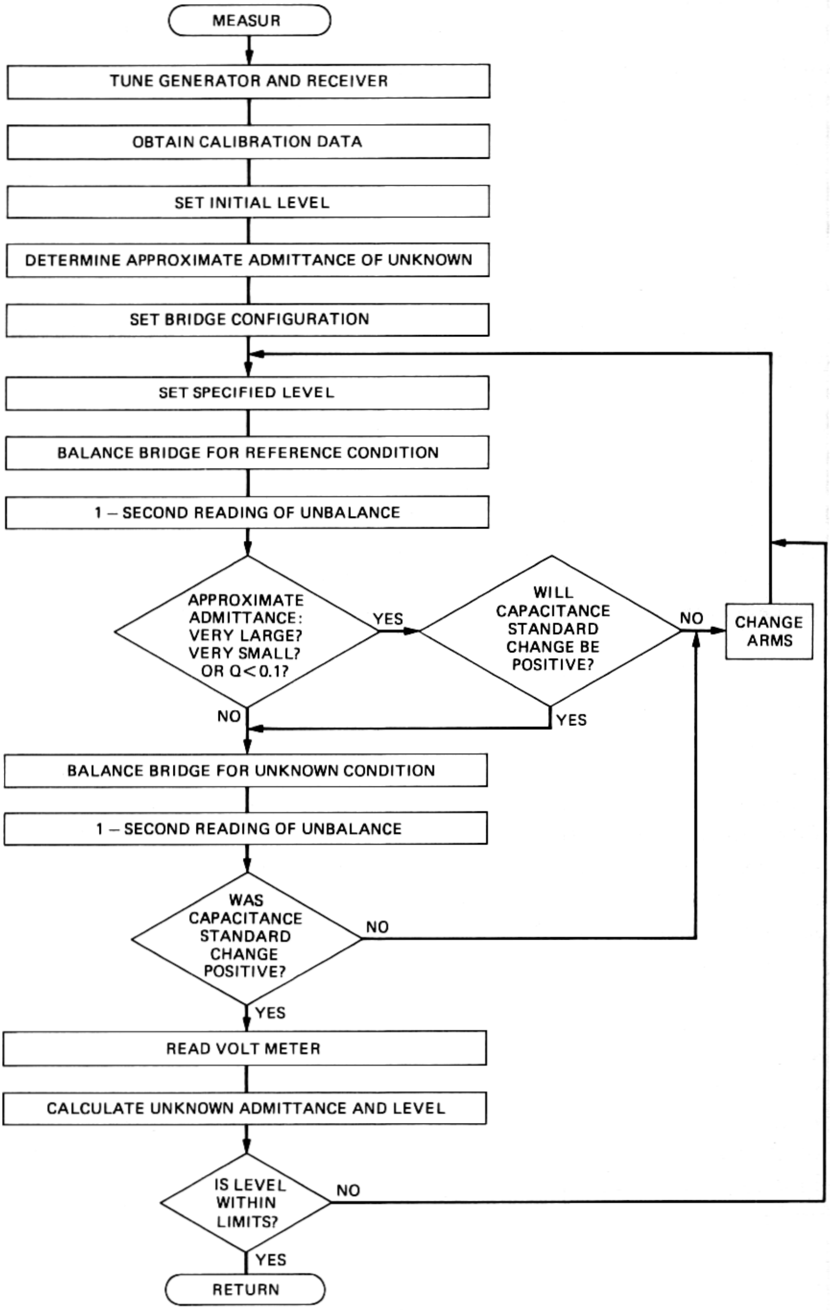


Fig. 11—Flowchart for the software module, MEASUR, that makes a measurement at a single frequency and signal level.

The approximate admittance of the unknown is calculated from measurements of the bridge output for four separate conditions, three of which serve to calibrate the system. All four conditions use the conductance standard in the C-D arm set to 9900 μS, which is approximately the admittance level between the small-impedance and small-admittance configurations. The three conditions used to calibrate the system are: a "short," an "open," and 6280 μS of susceptance in the A-D arm. The admittance values used for the "short" and "open" are based on the parasitic admittances of the switches, S1P and S2P, used to achieve the "short" and "open." The 6280-μS susceptance is obtained by an appropriate setting of the capacitance standard, and the actual susceptance and conductance of the setting are obtained from the standard's calibration data. The fourth condition uses the unknown in the A-D arm.

A small-admittance configuration is used if the conductance of the unknown is less than 90 percent of the 10,000-μS range of the conductance standard and if the magnitude of the unknown's susceptance is within 0.02 siemens and 75 percent of the range of the capacitance standard. Otherwise a small-impedance configuration is used.

When a small-impedance configuration is selected, the program chooses the largest series capacitor that is calibrated at the test frequency and that meets both of the following requirements: (1) the impedance of the capacitor and unknown in series must be greater than 20 ohms, and (2) the capacitance and conductance changes between the series capacitor alone and the series combination of the capacitor and the unknown must be within 75 percent of the range of the capacitance standard and 90 percent of the range of the conductance standard.

The arm into which the unknown is connected is determined by the sign of the unknown's susceptance.

After the bridge is set to the selected configuration and the bridge standards are set at values calculated to yield a bridge balance, the signal generator is adjusted to apply the requested level to the unknown. The level computations are based on the approximate value for the unknown and on the bridge configuration.

The bridge is then balanced at the reference condition. In the balancing process, the bridge's capacitance and conductance standards are iteratively adjusted toward balance, and the receiver gain is iteratively increased to maintain the receiver's output within the working range of the A/D converter. The changes to be made in the bridge standards are computed from the bridge's output, which is approximately proportional to the admittance difference between the A-D and C-D bridge arms. The constant of proportionality, in terms of siemens-per-volt, is computed after each change in the standards. This computation has to include the relative gains of the receiver before and after changing the standards. At frequencies above 45 kHz, the impedances of the filters following the rf attenuators are so poorly known (15 dB return loss) that the insertion loss of the last rf attenuator must be determined at the time of its being removed. This determination is made by adjusting the bridge unbalance to yield a suitably sized signal and reading the receiver's output with the attenuator in and then with it out.

When the bridge is very nearly balanced, the bridge's output signal is small and the resulting signal-to-noise ratio may be too small for accurate determinations of the siemens-per-volt. Accordingly, the siemens-per-volt is specifically calibrated for a final time when the bridge unbalance is within 0.5 percent of the total admittance across the C-D bridge arm. Between this degree of unbalance and complete balance, the siemens-per-volt will stay constant to within 0.25 percent.

The iterative process used to converge to balance is terminated when one of three conditions has been met: (1) the unbalance is within the smallest steps of the standards plus an allowance for noise; (2) the unbalance is within the rms deviation due to noise; or (3) there have been 50 iterations (a trouble condition).

The admittance of the remaining unbalance is calculated from a one-second reading of the receiver's outputs and the final siemens-per-volt calibration. So receiver's output signal is large enough to be read accurately and/or the output noise is well above the resolution of the A/D converter, the mean of the higher-valued receiver output is made greater than 5 volts or the standard deviation of the noisier receiver output is made greater than 0.2 volts. Then 700 pairs of samples of the outputs are taken over a one-second period.

A check is made of the correctness of the choice of bridge arm if the approximate admittance of the unknown differs by a factor of 100 or more from the 9900-μS admittance level used in determining the approximate value. For such admittances the determination of the approximate susceptance is not made with sufficient accuracy to assure consistently correct arm selection. Similarly the choice of arm is checked if the Q-value is less than 0.1 because the determination of the unknown's susceptance is not made accurately enough in the presence of relatively large conductance.

The check of the arm selection is made by leaving the bridge standards set at the reference balance; setting the S1P, S2P, and S3P switches for the unknown balance; and reading the receiver's output. If the susceptance change indicated by the output would require decreasing the setting of the capacitance standard to achieve balance, the unknown is switched into the other bridge arm and the setting of the signal level and the making of the reference balance are repeated.

When the arm selection is satisfactory after the one-second reading is complete, an unknown balance and one-second reading are made.

Then a second check on arm selection is made. If the capacitance of the unknown balance and its one-second reading is less than that for the reference balance, the arm selection is changed and the measurement is repeated starting at setting the signal level.

When the arm selection is proper, the voltage across the C-D arm of the bridge is read while the bridge is still set at the unknown balance. The admittance of the unknown and the signal level being applied to it are calculated. If the level is within 10 percent of the specified value, the measurement is complete and MEASUR returns. Otherwise, the signal level is reset and the measurement is repeated. However, this time the value of the unknown is known more accurately than the first time so the achieved signal level will be closer to the specified level.

4.3 User interaction and postprocessing

The simplest use of COZY consists of connecting the unknown to the bridge and entering a test frequency via teletypewriter dialogue with the program. After approximately 20 seconds, the measured value, the measurement uncertainty, and the signal level are typed out. In measurements where the signal level is not specified, as in this example, four volts are applied to the bridge.

Up to 15 frequencies and a signal level may be specified in a run. The signal level may be specified in terms of voltage across the unknown or current through it. Signal levels below the nominal minima of 50 millivolts or 0.5 milliamperes can be specified, but the measurement precision may be degraded by receiver noise. Above 15 MHz, the maximum signal levels decrease from 5 volts or 50 milliamperes to 0.4 volts or 4 milliamperes at 30 MHz.

The postprocessing options include having the results expressed in terms of a parallel model (e.g., parallel capacitance and conductance), a series model, and magnitude and angle. Also, Q-values may be requested. In addition, an inductor can be measured at several frequencies, and the change in effective inductance with frequency can be represented as a capacitance across the inductor.

When a cable or fixture is used to attach a component to the bridge, one or two measurements (at each frequency in the case of a frequency run) may be used to characterize the cable. Then, after the component has been measured, the effects of the connecting cable or fixture are automatically corrected for. The characterization measurements are of the open-circuit admittance and/or the short-circuit impedance of the cable or fixture. The circuit model for the cable or fixture is that of a uniform transmission line.

The teletypewriter, a line printer and/or magnetic tape may be specified as the output medium.

V. ACCURACY

5.1 Accuracy for measuring the impedance/admittance of components

Figure 12 shows on a reactance chart contours of ±0.05-, ±0.25- and ±1-percent uncertainties in the measurements of the inductance or capacitance of components having large Q-values. Figure 13 shows contours for ±50- and ±250-microradian uncertainties in measuring the loss angles of such components. These loss angle uncertainties

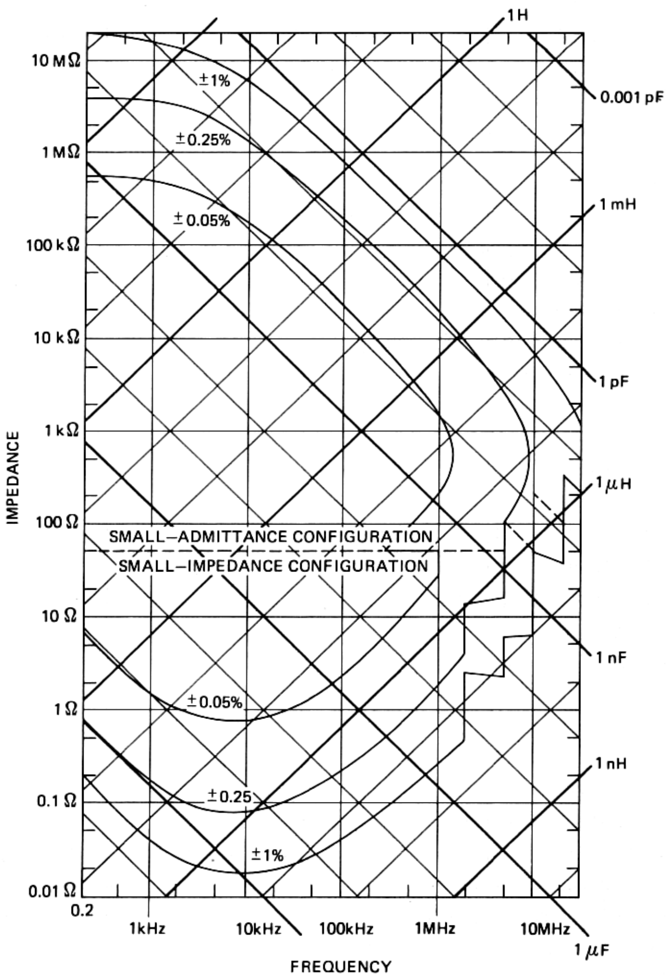


Fig. 12—Inductance/capacitance measurement uncertainty for high-Q components.

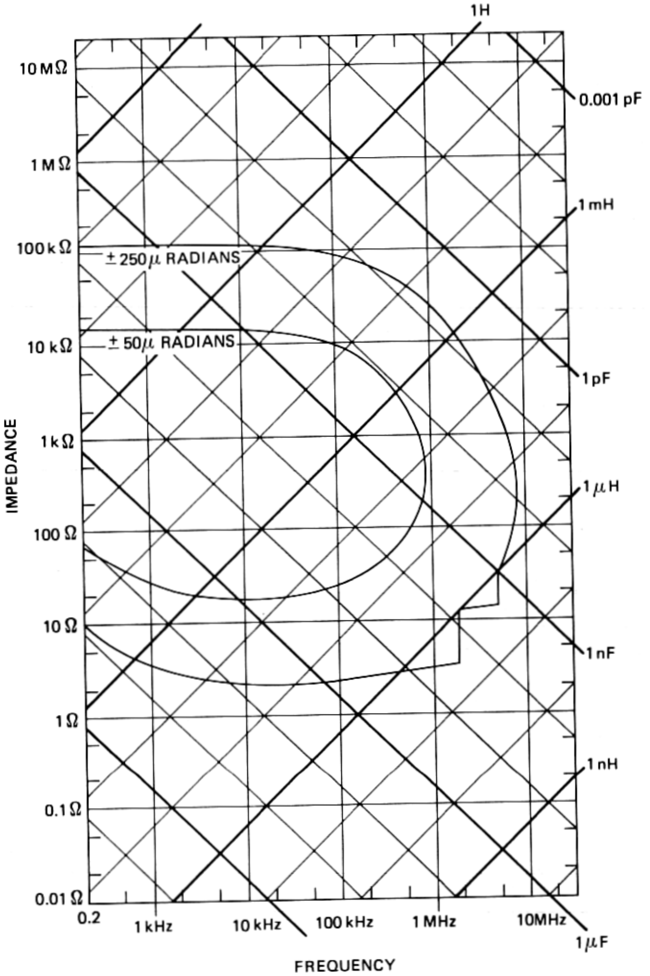


Fig. 13—Loss angle measurement uncertainty for high-Q components.

correspond to ±5 percent uncertainty in measuring Q-values of 1000 and 200. Figure 14 shows ±0.05-, ±0.1-, and ±1-percent uncertainty contours for measuring the resistance or conductance of components having small Q-values. Figure 15 shows contours of ±100-, ±1000-, and ±10,000-microradian uncertainties in measuring the phase angle of these components. For clarity all four figures show smoothed contours for the small-impedance configurations. The exact contours would have small sawtooth wiggles as successively smaller series capacitors were used with increasing frequency. Also small differences between the uncertainties for measuring inductors and capacitors have been ignored.

The confidence factor for the uncertainty contours is 75 percent. That is, at a contour there is a 75 percent probability that the error in a measurement is less than the uncertainty associated with the contour. Well within a contour the confidence factor is much higher than 75 percent. For example, well within the ±0.05 percent contour of Fig. 12 the uncertainty approaches ±0.02 percent and the probability that the error is within 0.05 percent approaches unity.

The uncertainties shown in the figures are for voltages across the C-D bridge arm between 0.05 V and 5 V. For small-admittance components, these voltages correspond to test voltages across the component

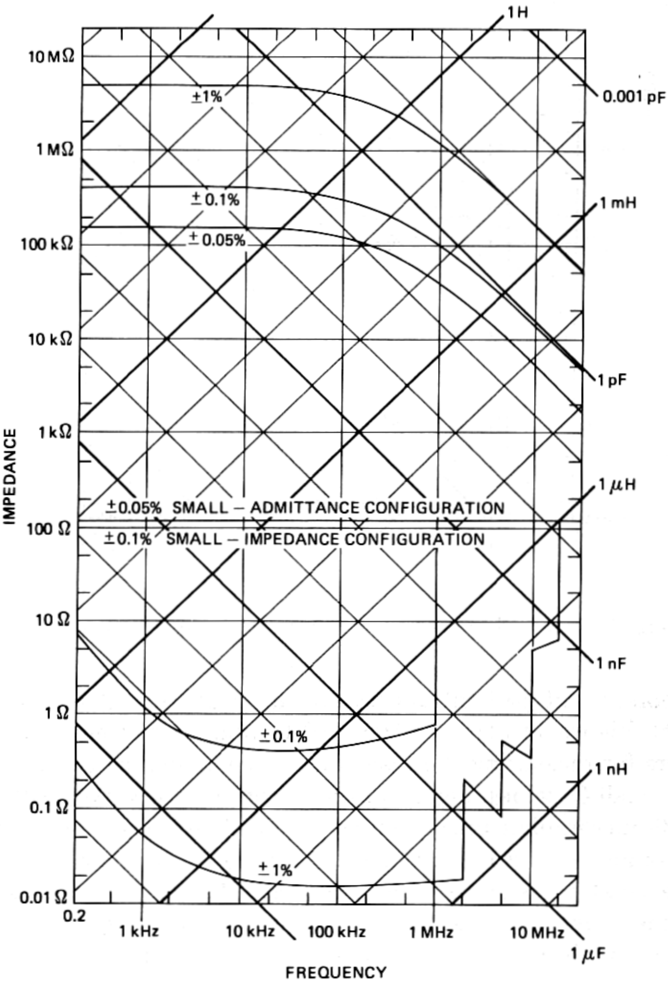


Fig. 14—Resistance/conductance measurement uncertainty for low-Q components.

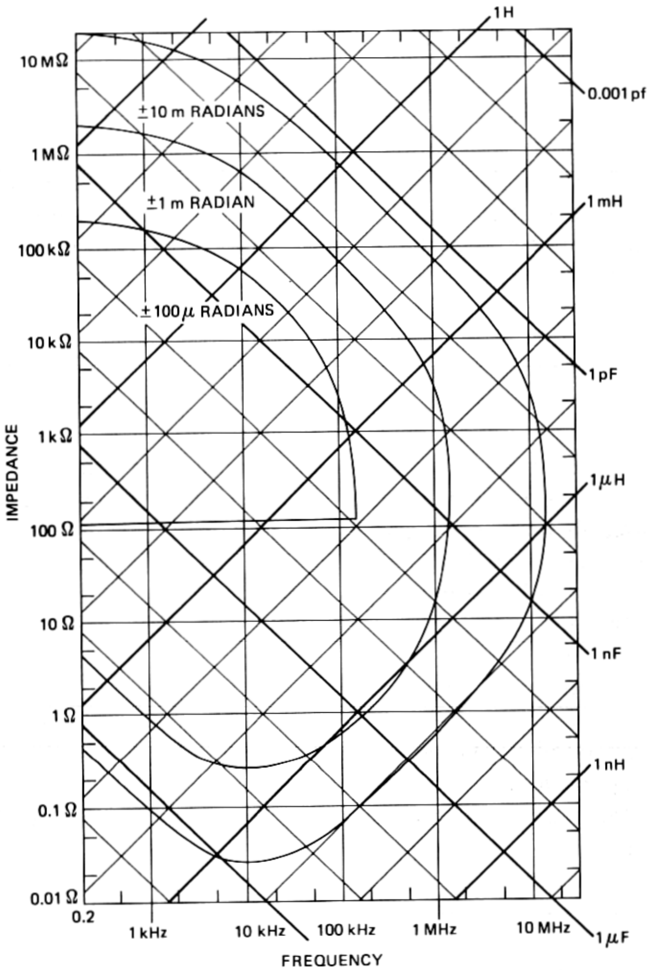


Fig. 15—Phase angle measurement uncertainty for low-*Q* components.

between 0.05 V and 5 V; for small-impedance components, to test currents through the components of approximately 0.5 mA to 50 mA.

For components measured with the small-admittance configurations, the basic measured quantity is the admittance difference between a measurement of the component plus connecting leads and a measurement of the open-circuited leads. This admittance difference can be translated from COZY's binding posts to the other end of the connecting leads by correcting for the effect of the leads' series impedance. This impedance is obtained by measuring the leads with a short circuit in place of the component. Figures 12 through 15 apply to the admittance difference as seen either at COZY's binding posts or at the component's end of the connecting leads.

For components measured with the small-impedance configurations, the uncertainty contours are for the impedance difference between a measurement of the component at the end of connecting leads having an inductance of 0.1 μH or larger and a measurement of a short-circuit at the end of the leads. This requirement for a minimum 0.1-μH inductance in the connecting leads arises because the condition used for the reference balance differs from that for the unknown balance by the closing of the switch, S1P in Fig. 4, across the binding posts. If the impedance connected to the binding posts is small compared to that of the switch, then the impedance difference between the unknown balance and the reference balance is insensitive to the impedance connected to the binding posts. Since the inductance of the switch is 0.025 μH, using connecting leads having inductances of 0.1 μH or more provides good sensitivity for measuring the inductance of the leads with the component connected to them and the inductance of the leads with the short-circuit connected to them. In addition, with 0.1-μH leads, errors in the calibration of the impedance of the switch have approximately equal effects on the measurements of the leads with the component connected and of the leads with the short-circuit connected. As a result, errors in the calibration of the switch's impedance have only slight effects on the impedance difference between the measurements.

For components measured with the small-impedance configurations, the uncertainty contours also apply to the impedance difference after being translated to the component's end of the connecting leads by correcting the above impedance difference for the connecting leads' shunt admittance, which is obtained by measuring the leads open-circuited.

Figures 12 through 15 were obtained from an analysis of the effects on measurements of the uncertainties in the individual quantities entering into the measurement results. The uncertainties for these quantities were arrived at by a combination of: (1) analysis of the uncertainties in the determinations of the individual quantities by the calibration processes; (2) intercomparisons of the measurements of the same unknown made in different ways (e.g., made with both the small-admittance and small-impedance bridge configurations); (3) measurements of some standards whose admittances are known by other means (e.g., specially constructed parallel plate capacitors and the inductance standards of Ref. 1); and (4) much use of the bridge for the past eight years.

5.2 Sources of uncertainty in small-admittance configuration measurements

The sources of uncertainty for measuring a component's capacitance or inductance using the small-admittance configuration are in the capacitance calibrations of the bridge standards and in the inductance calibration for the impedance, Z_{CH} in Fig. 9, in series with the binding posts. The uncertainty in the calibration of the capacitance of the capacitance standard at frequencies below 100 kHz is ±0.02 percent. This value represents the uncertainties due to aging and to transferring a calibration from the Type 12 capacitance bridge. The basic uncertainty of the Type 12 bridge is ±0.005 percent. Checks of the COZY bridge show its variations with time to be less than ±0.01 percent. At frequencies above 4 kHz the end term uncertainty in the capacitance calibration for large capacitances is ±0.02 pF and results from: mutual capacitances between the standard's decades; accumulation in the calibration values for the larger steps of the small uncertainties in each of the many balances that contribute to their calibrations; and there being several capacitance and conductance decades involved in any one balance setting. At frequencies below 4 kHz the end term uncertainty corresponds to a susceptance resolution of ±0.5 nS.

An uncertainty of ±5 nH is assigned to the calibration of the parasitic series impedance, Z_{CH}. However, it is not known how much of this comes from the uncertainty in the value for Z_{CH} and how much comes from mutual inductances between the decades of the capacitance standard.

The 0.02-pF and 5-nH uncertainties produce uncertainties in the measurements of the external standards used to determine absolute calibrations for the bridge's capacitance standard. The minimum measurement uncertainty occurs when the individual contributions of these uncertainties are equal. At the optimum admittance level the resulting calibration uncertainty is $\pm 0.013M$ percent, where M is the calibration frequency in megahertz.

For measurements of unknowns having small Q-values there is an additional capacitance uncertainty of $\pm 0.06M/Qx$ percent, where Qx is the Q-value of the unknown. This uncertainty results from a 100-ps time constant uncertainty in the calibration of the phase angle of the bridge's conductance standard.

The major sources of uncertainty in the measurement of conductance using the small-admittance configurations are:

- ±0.02 percent and ±0.002-μS uncertainties in the calibration of the conductance standard
- ±20 microradians and ±5-ps time constant uncertainties in the calibration of the loss angle of the capacitance standard. Actually, part of the 5-ps uncertainty may be due to uncertainty in the time constant of the bridge ratio. These uncertainties are the major uncertainties in measuring large Q-values.
- $\pm 0.006M$-μS conductance resolution (corresponding to ±0.001 pF), where M is the frequency in megahertz.
- $\pm 0.001\sqrt{M}$-ohm uncertainty in the resistance of Z_{CH}.

5.3 Sources of uncertainty in small-impedance configuration measurements

For measurements using the small-impedance configurations, the uncertainties in the calibrations of the capacitance and conductance standards produce corresponding uncertainties in the measured admittance difference between the unknown and reference balances and in the calibration values for the series and shunt admittances, Y_K and Y_{ET} in Fig. 10. In addition, the measurement of the admittance difference between the balances has an end term uncertainty of ±2 parts per million of the series admittance, Y_K.

The end terms for the impedance difference between an unknown and a short circuit at the end of 0.1-μH connecting leads are $\pm[(0.2 \text{ to } 0.7) + 0.016/M]$nH and $\pm[(0.2 \text{ to } 0.5) + 0.6M]m\Omega$. The minimum values pertain to components having impedances small compared to the impedance of the connecting leads. The maximum values are for component impedances large compared to that of the connecting leads.

VI. AUTOMATIC MAINTENANCE AIDS

The overall system includes automatic aids for maintaining the calibration of the bridge standards and the operation of the hardware. Of particular importance are the aids for calibration maintenance. Errors in the calibration typically do not interfere with the measurement process to cause error messages, as hardware faults do, and so the only way to have continuing confidence in COZY's accuracy is to check the calibration on a routine basis. However, calibration checks involve so many bridge balances and computations that to make them practical on a routine basis requires automation.

The calibration maintenance aids include a group of programs that check for changes in the admittances of the steps of the capacitance and conductance standards. One program does a step-up calibration of the bridge standards for up to six successive times. The average values and the scatters for the capacitance and conductance of each step are printed out. Examination of these results shows whether the system is performing well and whether the reproducibilities of the steps are satisfactory.

Another program performs an element by element subtraction between the values of a new calibration and of the calibration being used for measurements. Examination of the results shows whether the calibration being used is satisfactory.

Still another program automatically measures the series and shunt admittances, Y_K and Y_{ET}, of the small-impedance configurations. These results can be compared with the existing calibrations.

The aids for maintaining the hardware include monitors at the 13 power supplies and at 29 points within the generator and receiver. The outputs of the monitors can be read by the A/D converter and are used by a hardware checking program to measure: the voltages of the power supplies; the gains and losses of the amplifiers and attenuators; the in-band transmissions and out-of-band rejections of the low pass filters; and various signal levels. The program can be run to check that the functions and levels are within limits or to print out the results of the measurements. A go/no-go check of the functions and levels takes five minutes. When the generator or receiver is malfunctioning, a diagnosis of the measurements can lead to localizing the fault to within four active components.

A second hardware checking program tests the operation of the relays in the small-step decades of the bridge's and step-up unit's capacitance and conductance standards. The special mercury-wetted switches, which use platinum leads, are not as reliable as the standard switches, which use only magnetic alloy leads; the platinum-to-glass seal is fragile. As a result, some relays have failed. Typically these relays were in the bridge's small-step decades, which contain the most used relays. A few of these failed relays gave troubles by becoming slower than the settling times used in the measuring program. In these cases, static tests of relay operation were not sufficient.

VII. MEASUREMENTS OF ENVIRONMENTAL COEFFICIENTS AND DISACCOMMODATION FACTORS

7.1 Environmental coefficient measurements

To make environmental coefficient measurements the user connects the components to sample boards in the environmental chamber, connects a coaxial cable from the sample boards to the bridge's binding posts and enters via dialogue the desired measurement conditions, post processing of the measurement results and output media. Up to six components may be connected to each of three sample boards, with all the components on a board having the same nominal impedance. One signal level and up to 20 test frequencies may be specified for each board. Up to 20 environmental conditions, i.e., combinations of dry bulb temperature and relative humidity, may be specified. For each environmental condition there may also be specified a soak time, and whether the rate of temperature change is to be kept below 1° Celsius per minute (to avoid thermal shock).

For each environmental condition the computer passes to the chamber's microprocessor the dry bulb temperature, dew point, soak time, and whether the rate of temperature change is to be restricted. Then the computer repetitively queries the microcomputer concerning whether the specified conditions have been met. When the conditions have been met, COZY makes the specified impedance/admittance measurements and the computer then passes to the microcomputer the next set of conditions. While the environmental conditions are being achieved, the computer and bridge unit are free for general purpose measurements.

Each of the three sample boards in the environmental chamber has eight pairs of binding posts. Six of the eight pairs are for samples, the seventh pair has a short circuit across it and the eighth pair is left open. The short-circuited and open-circuited binding posts are used to obtain corrections for the effects of the series impedances and shunt admittances of the cables, switches and sample board circuitry between the bridge's binding posts and the binding posts to which the samples are connected.

The sample boards are made from teflon impregnated sheets of woven fiberglass. Within the chamber the upper side of each quarter-inch thick board is plated with 3-mil copper that serves as the ground plane for eight strip lines on the board's under side. The strip lines provide the connections to the board's "high" binding posts. The thermal conductivity from the binding posts to the outside of the chamber is low enough so that at steady state the temperatures of the binding posts are within 0.1° Celsius of the chamber's temperature. The difference between the inductance and resistance of the strip line to a board's short-circuited binding posts and the inductances and resistances of the strip lines to the board's sample positions are corrected for in data reduction via stored values for these differences. Similarly, the capacitance differences between the open-circuited strip line and the strip lines to the sample positions are corrected for in data reduction. However, the capacitance differences vary nonreproducibly with temperature, humidity, and recent history. These nonreproducible variations cannot be corrected for and therefore introduce errors in environmental coefficient measurements. The worst case variation over the environment range of the chamber is ±0.2 pF.

Increased speed for environmental coefficient measurements was achieved by changing the software to take advantage of the similarities of many of the measurements. All the samples on one board are required to be nominally the same. Also, the impedances of the samples do not change drastically with the changes in environmental conditions. Consequently, the complete measuring process is used only for the first environmental condition and then only for the short-circuit, the open-circuit, and the first sample positions on each sample board. For the second through sixth sample positions only the unknown balances are made; the bridge configuration information and reference balance data are retained from the first sample position. For the second and following environmental conditions the bridge configuration information obtained during the first environmental condition is used to set up the bridge for balancing. As a result of the decreased number of reference balances and determinations of approximate values for the unknowns, the average time for a measurement is less than 10 seconds, versus about 20 seconds for a general purpose measurement.

Increased accuracy for environmental coefficient measurements was achieved by changing the software so that measurements of small changes in admittance will not involve changes in the settings of decades having relatively large steps. Otherwise, small fractional changes in the admittances of the large-step decades could cause large errors in the measurements of small changes in admittance. This avoidance of changes in the large-step decades is done by making two balances instead of one when the bridge can be balanced at more than one setting of the standards. In these cases one balance uses zeros in the setting and the other balance uses tens. Thus, if a balance could be made at a setting of 2-0-0.-0-0 (i.e., the 100-pF per step decade set to two; the 10-pF, to zero; the 1-pF, to zero; etc.), it would be. However, a second balance would also be made at a setting of 1-9-9.-9-10. (For simplicity, in this example it is assumed that the actual value of a setting equals its nominal value.) The setting of the standards and the admittance at balance would be saved for both balances. Then, if at the next temperature the setting at balance were higher, say 2-0-0.-0-9, the difference would be calculated with respect to the 2-0-0.-0-0 setting. But if the setting were lower, say 1-9-9.-9-1, the difference would be computed with respect to the 1-9-9.-9-10 setting.

7.2 Disaccommodation factor measurements

Measurements of the disaccommodation factors of ferromagnetic materials are also made using the environmental chamber. The user specifies temperature, relative humidity, soak time, temperature rate restriction, measurement frequency, and whether measurements are wanted 100 and 1000 minutes after demagnetization. (Measurements 1 and 10 minutes after demagnetization are always made.) In addition, for each sample board the user specifies peak demagnetization current and test signal level.

In the measurements the temperature is held fixed at the user-specified value, the components are individually demagnetized, and their inductances are measured at the appropriate times after demagnetization. Demagnetization is done with a 60-Hz current that decreases linearly to zero in 15 seconds. The software for these measurements makes use of the zero- and ten-settings to optimize the accuracy for small admittance changes. Also, the software includes a reorganization of the major blocks of the measurement process to make the time sequencing of demagnetizations and measurements so efficient that the demagnetizations and one-minute measurements of all 18 samples are done before the first ten-minute measurement is to be made.

VIII. SUMMARY

The computer-operated impedance/admittance bridge (COZY) is an easy-to-use facility that provides fast, highly accurate measurements over a wide impedance range at frequencies between 200 Hz and 30 MHz. The accuracy is comparable to that achieved with specially developed manual bridges, but the expertise, care, and time required of the user are a tenth to a hundredth of that required for manual bridges. Also, the expertise and effort required to check and maintain the calibrations are similarly less. This is especially true since COZY's admittance-frequency coverage exceeds that of five manual bridges.

In addition to high accuracy, COZY also provides high resolution for measuring small changes in impedance/admittance. This attribute has proved to be very valuable in studies of stability versus shock and vibration and also versus time, and has been capitalized on by the addition of hardware and software that provide automatic measurements of environmental coefficients and disaccommodation factors.

The speed, accuracy, and resolution of COZY have been extensively used in the development and evaluation of materials, structures, and complete components for ferromagnetic inductors and transformers. In this work COZY has permitted measurements and evaluations that would have been otherwise impossible.

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