AUTOMATIC CAPACITANCE MEASURING SYSTEM

ROGER HALA

SAN DIEGO DIVISION
THE BISSETT-BERMAN CORPORATION

TECHNICAL REPORT AFFDL-TR-71-101

AUGUST 1971

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICE

AD-739556

AUTOMATIC CAPACITANCE MEASURING SYSTEM

ROGER HALA

FOREWORD

This research and development program was performed by the San Diego Division of Bissett-Berman Corporation, San Diego, California, under Air Force Contract F33615-69-C-1298. The contract was initiated under Project 1347, "Structural Testing of Military Flight Vehicles", Task 134702, "Measurement of Response of Aerospace Structures."

The work was directed by Neil Brown. The report was prepared by Roger A. Hala. This project was initiated by the Air Force Flight Dynamics Laboratory, and was administered under the technical coordination of James L. Mullineaux, AFFDL/FBT.

Acknowledgement is given for the assistance provided by Ronald Beattie, Research Assistant who fabricated, evaluated, and tested the capacitance measurement system.

This document was submitted in February 1971. The report covers work conducted from December 1968 to February 1971 and is the final report under Contract F33615-69-C-1298.

This technical report has been reviewed and is approved.

Robert L. Cavanagh
Chief, Experimental Branch
Structures Division
Air Force Flight Dynamics Laboratory

ABSTRACT

This report describes the development of an automatic capacitance measurement system. The system was specifically designed to be compatible with a capacitive strain gage working in ambient temperatures up to 1500°F. The progression of the development yielded a system capable of measuring three terminal capacitors at a distance of up to 150 feet. Two systems were constructed and delivered to the Air Force Flight Dynamics Laboratory. The system measures capacitances from 10 to 30 pf and automatically balances the loss component. Four frequencies of operation are selectable for system operation. The outputs of the system are a D. C. voltage of 50 mv/pf and a digital indication of capacitance. The results of tests indicated the automatic measurement of remote capacitance to a high degree of accuracy is, in every respect, technically practical. All of the target specifications were not met; however, the performance anomalies occurred at the extremes of measurement.

CONTENTS

LIST OF ILLUSTRATIONS

TABLES

SECTION I

INTRODUCTION

Development of processes enabling fabrication of high temperature capacitance strain gages and the realization that future programs in the aircraft, missile and space environments will require measurements in more detail and in more stringent environments have necessitated the development of a means of remotely monitoring the gages. The desirability of miniature gages is obvious and, due in part to the miniature size, the capacitance changes which indicate strain levels are also miniature.

In December 1968 Bissett-Berman Corporation began a program to develop an automatic capacitance measuring system under Contract F33615-69-C-1298. This capacitance measuring system was specifically designed to be operative with a high temperature capacitance strain gage developed under Contract F33615-67-C1448, and fully described in report AFFDL-TR-68-27 (Reference 1).

The remote monitoring of the capacitive strain gage provided a number of unique problems which were investigated in an initial study and design phase and refined during a hardware realization phase. The techniques that were developed or refined to meet the particular objective of measuring one design of capacitance strain gage are suitable for use with similar designs and can be directly applied for remote measurement of any three terminal capacitor.

SECTION II

TARGET SPECIFICATIONS

1. Gage Performance

The performance of the capacitance strain gage, and thus the input for the automatic capacitance measuring system, was specified as:

a. The initial capacitance will be between 10 and 30 picofarads.

b. The total capacitance change will be ±2 picofarads.

c. The maximum rate of change of capacitance will be ±0.2 picofarads per second.

2. System Performance

The performance of the automatic capacitance measuring system as well as the configuration of the system was specified as:

a. The prototype capacitance measuring system shall consist of two individual capacitance bridges and one digital readout instrument.

b. The accuracy of the system shall be ±0.1% of full scale.

c. The resolution of the system shall be 0.002 picofarads.

d. The drift rate of the system shall not exceed 250 microvolts per hour.

e. The system shall operate from a 115 ±10 volts AC, 60 hertz power source.

f. The system shall be modular, compact, and rack mounted.

g. The design and development of the system shall reflect the consideration of such variables as temperature, vibration, humidity, and other ambient conditions normally expected to be encountered in a large structures test laboratory without atmospheric control.

h. The system shall be designed in accordance with the highest standards of commercial practice. Consideration shall be given to design simplicity and ease of maintenance during in-service usage.

3. Capacitance Bridge Performance

Whereas the capacitance bridges are the key to successful operation of the system they were specified so as to have the maximum of versatility and maintain reasonable simplicity:

a. Each of the two capacitance bridges shall be separate and independent channels.

b. Each bridge network shall have its own stable oscillator that is controllable from 1 kilohertz to 1 megahertz in a minimum of five steps selected by an easily accessible control.

c. The bridge network shall contain controls for manually balancing the bridge initially.

d. The output of the bridge network shall be an analog signal of 100 microvolts DC per 0.002 picofarad change.

   (1) The analog signal shall be available at convenient terminals for connection to high impedance (1 megohm minimum) recording devices external to the system.

   (2) The analog signal shall also be available for the digital readout instrument in the prototype system. A switch shall be provided so that the output from either of the two bridge networks may be selected for presentation on the digital readout instrument.

   (3) The output shall not deviate from a straight line more than ±0.1% of full scale with a linear change of capacitance.

   (4) The output shall increase with an increase in capacitance.

e. The bridge network shall eliminate the effects of stray capacitance between the strain gage signal leads and other conductors.

f. The bridge network shall have provisions for measuring and/or nulling out distributed capacitance of up to 30 picofarads between the two strain gage signal leads.

g. After the initial balancing of the bridge network, the system shall automatically produce a change in output with a change in capacitance and it shall not be necessary to manually control any part of the bridge network in order to achieve accurate readings.

h. To check the bridge operation, each bridge network shall have at least one standard capacitor which can be switched into the network in lieu of the strain gage.

i. Each bridge network shall incorporate a means of electrically simulating a known strain in the strain gage.

j. Each bridge network shall have provisions for measuring the total capacitance of the strain gage at the no-load or zero strain condition.

k. Each bridge network shall have one active (strain gage) arm.

l. Since the capacitance strain gage is designed for use up to 1500°F, it is not advisable to locate any of the bridge network in the vicinity of the gage.

4. Readout Performance

A visual indication of performance was desirable and the inclusion for a direct digital indication was specified as:

a. The readout shall have five digits plus sign. Polarity switching and indication shall be automatic.

b. The readout shall indicate directly in units of picofarads.

c. The full scale range shall be ±99.999.

d. The visual indication shall be easily read and interpreted.

SECTION III

SYSTEM DESIGN

1. System Description

The final configuration of the capacitance measurement system is as shown in Figures 1 and 2. It is comprised of five major sections. The sections are:

a. Control Electronics

b. Transformer Networks

c. Automatic Capacitance Balance Network

d. Automatic Quadrature Balance Network

e. Balance Amplifier

Each section performs a particular interrelated function.

The control electronics is comprised of the circuitry necessary to condition the output of the balance network and make it suitable for recording or digital display. These circuits provide the necessary scale factors and the ability to give total sensor capacitance, differential sensor capacitance, and strain as system outputs. The control electronics also contain a series of switches which select the operating mode of the system.

The transformer networks are used to scale voltages, provide accurate voltage ratios, and provide accurate phase related signals. Two transformers are used in the system. One is used in the low frequency ranges and the second in the higher frequency ranges.

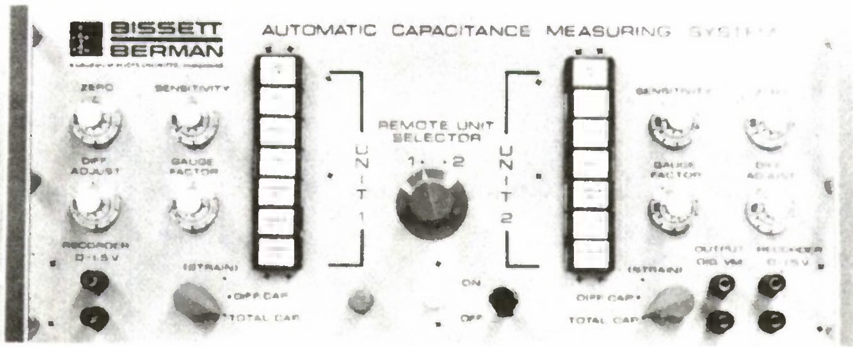
The automatic capacitance balance network is the main capacitance bridge and the portion of the system which converts the gage capacitance into a D. C. signal. It contains the four arm capacitance bridge, precision D. C. reference supplies, the thermistor balance network, interconnecting coaxial cables, and the reference and standard capacitors.

The automatic quadrature balance network senses the quadrature component after balance of the in-phase signal and automatically creates a loss component across the reference capacitor which cancels the loss component in the sensor. It is comprised of a phase shift network, detector and drive amplifier. The drive amplifier supplies power to a light source which is used in conjunction with a photocell to simulate losses.

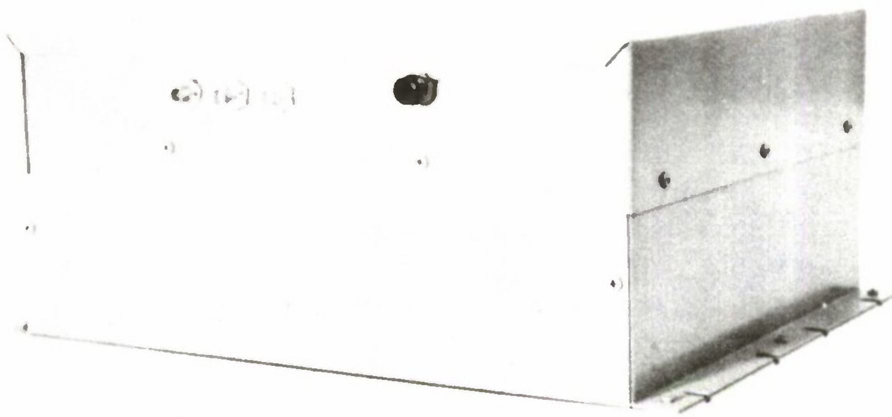
The balance amplifier provides the operating frequency determining components and a field effect transistor input, 5 stage, A. C. amplifier. This amplifier is the gain source used within the feedback loop.

2. Control Electronics

The control electronics as shown in Figure 3 has a D. C. amplifier with a fixed gain of 20 as an input. This amplifier has a Fairchild type 726 temperature



CONTROL PANEL



REMOTE ELECTRONIC UNIT

DIGITAL VOLTMETER

Figure 1 Automatic Capacitance Measuring System

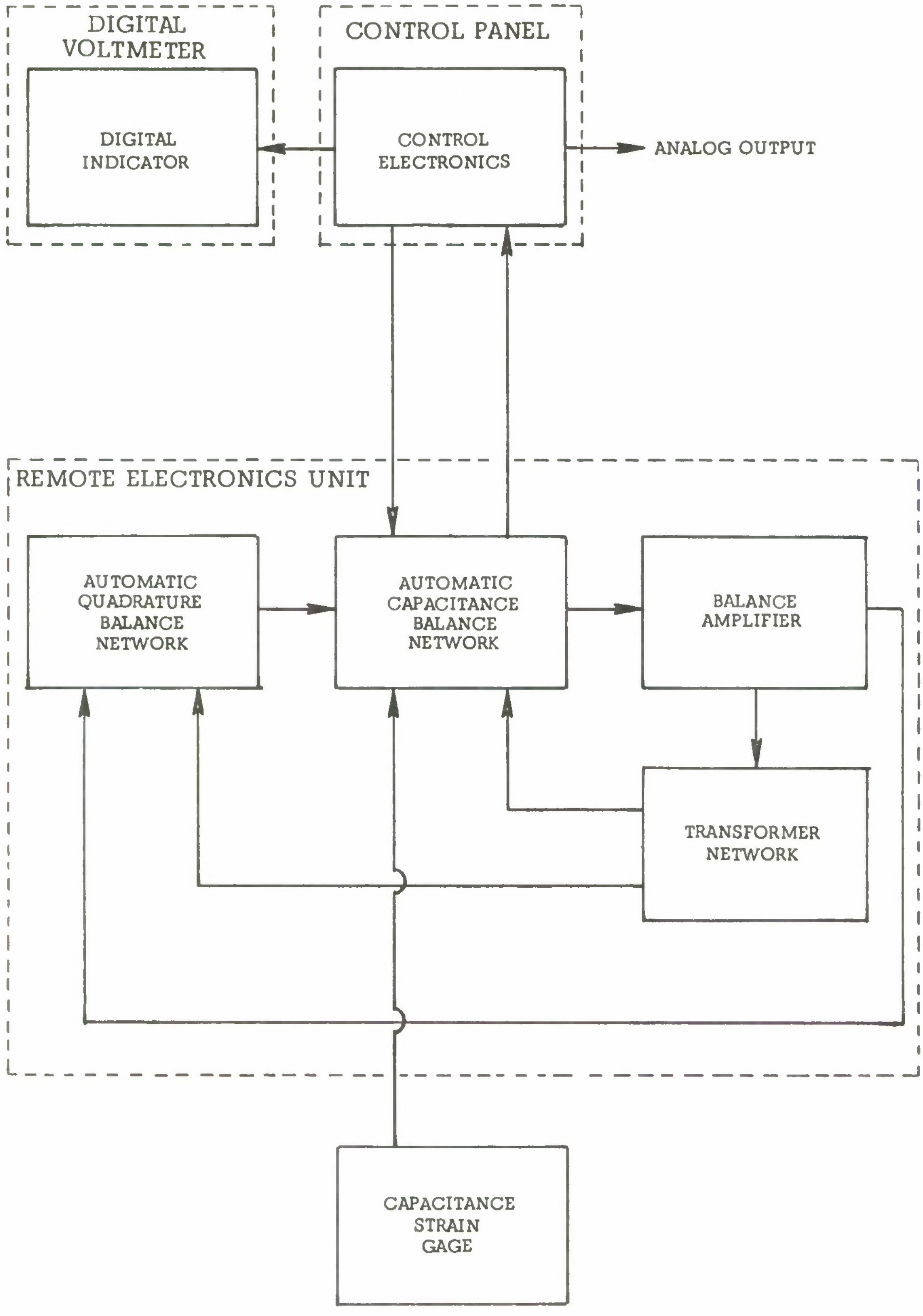


Figure 2. Automatic Capacitance Measuring System Block Diagram

controlled transistor differential pair input and is followed by a Fairchild 709 amplifier. The combination is connected in the non-inverting mode. The gain is adjustable from 19.2 to 21.1. The offset is also adjustable over a ±.63 VDC range.

A direct current reference signal is generated by a zener voltage from the precision reference source in the capacitance balance network for use when measuring differential capacitance and strain; another reference is generated from the supplies for use when measuring total capacitance. The references are buffered with a 709 amplifier connected in the non-inverting unity gain mode. The buffered reference and the outputs of the 20 times amplifier are summed in another non-inverting 709 amplifier with a gain which can be varied from 1 to 1.1. This adjustment provides for sensitivity of the system.

The switches available in the control electronics provide the various outputs to the digital indication and the supply voltages to reed relay coils which control functions in other portions of the system.

3. Transformer Networks

As indicated earlier the transformers provide an accurate means of generating two equal but out of phase voltages. The system uses two transformers. The first is a low frequency transformer used at 1 KHz, 5 KHz and 30 KHz. It is comprised of a toroidal core with 3/50 turn windings and 2/30 turn windings. The high frequency transformer is wound on a toroidal core with 3/5 turn windings and 2/3 turn windings, and is used at 150 KHz.

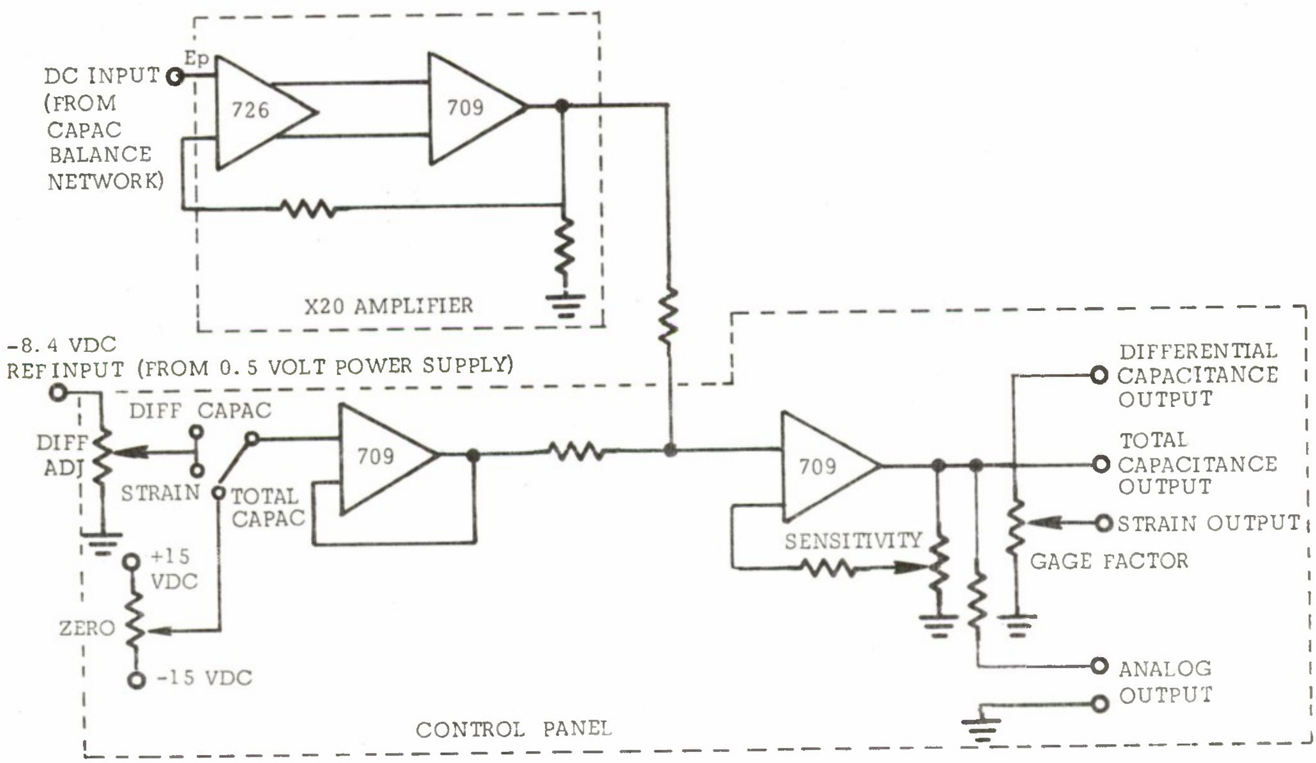


Figure 3. Circuit Diagram Control Electronics

Two of the higher numbered windings are used to drive the sensor and reference capacitor, the third is used as the primary. The remaining windings are used to drive the quadrature balance circuits.

Figure 4 shows the phasing relationship of the windings. Particular care was taken on the high frequency transformer to reduce interwinding capacitance, i. e. bifilar wound.

4. Automatic Capacitance Balance Network

The automatic capacitance balance network forms the heart of the capacitance measurement system and it was in this area that the majority of the preliminary investigations were conducted, and the majority of problems anticipated.

The performance of the capacitance balance network can be broken into two areas. First is the A. C. operation of the circuitry which enables measurement of capacitance and secondly the D. C. portion which generates an analog voltage as a resultant of the A. C. action. Thus, the actual capacitance measurement is carried out using A. C. and the output is a D. C. analog.

a. A. C. Operation

The target specification required a distance of 150 feet between the gage and the visual output. This requirement led to serious difficulties at 1 MHz. At these high frequencies, a cable length of

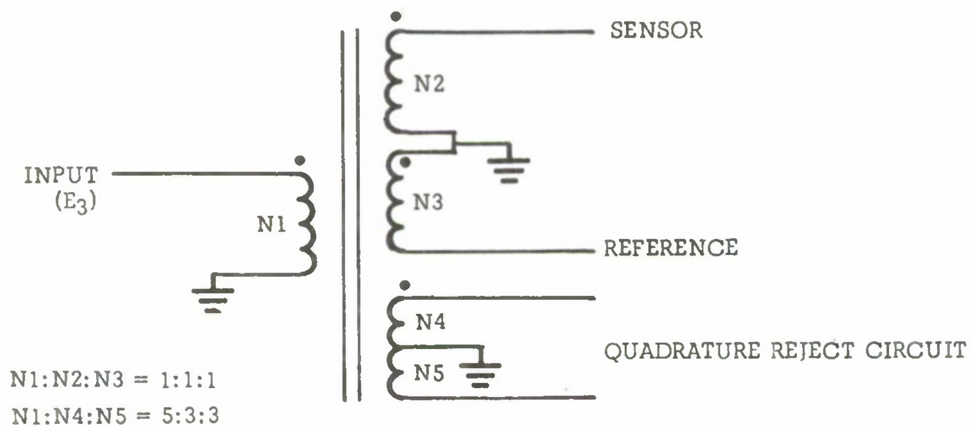


Figure 4. Transformer Diagram

150 feet is an appreciable fraction of a wavelength. The velocity of propagation of a signal on a coaxial cable is given by the following:

$$vp = \frac{C}{\sqrt{\epsilon}} \qquad (1)$$

where C = velocity of light (3×10^8 meters/sec)

ϵ = dielectric constant of insulation in the coaxial cable connecting the sensor to the bridge

For a nylon cable, ϵ will equal about 2.2, resulting in vp equal to about 2×10^8 m/s. This corresponds to a wavelength (λ) given by

$$\lambda = \frac{vp}{f} \quad \text{where } f = \text{frequency} \qquad (2)$$

at 1 MHz $\quad \lambda = \dfrac{2 \times 10^8}{1 \times 10^6} = 200$ meters

$= 660$ feet

The 150-foot length would be equal to 150/660 = 0.23 wavelengths. This, in turn, results in serious phase shift and standing wave problems unless careful matching of cable lengths and impedance is performed. Most of the other techniques described in the literature for doing capacitance measurements at these frequencies involved systems where the measuring bridge and the capacitor were in very close proximity, thus avoiding the problems cited above.

Figure 5 shows a schematic of a basic bridge. The detailed study performed on this bridge circuit, particularily with respect to the phase and amplitude relationships on the transmission line used to connect the capacitance strain gage transducer to the bridge circuit, resulted in some very pertinent conclusions. These clearly showed that it is virtually impossible to perform accurate measurement of capacitance at the end of a transmission line whose length approaches 1/4 wavelength of the excitation frequency. At 1 megahertz a 150 foot cable is effectively 1/4 of wavelength when one takes into account the dielectric constant of the insulator.

A study of the following equations and numerical data will show that it was necessary to restrict the distance between the strain gage capacitor and the bridge to no more than 50 feet. This implied that the bridge components be mounted in a remote unit located 100 feet from the rack mounted readout equipment with connecting cables carrying only D. C. signals and D. C. power supply voltages.

A study of the phase and amplitude relationships between the various voltages shown in the basic bridge circuit (Figure 5) led to the following conclusions:

(1) There is a phase shift between E_1 and E_{g1} which is directly proportional to the length of the co-ax cable, assuming that it is terminated with its characteristic impedance Z_o. The relationship between E_1 and E_{g1} is given by the following:

$$E_1 = E_{g1} e^{\sqrt{ZY} \cdot L} \tag{3}$$

where E_1 = (See Figure 5)

Eg_1 = (See Figure 5)

Z = series inductance per unit length

= .093 x 10^{-6} henries per foot (typical)

Y = shunt capacitance per unit length

= 30 picofarads per foot (typical)

L = length of cable (feet)

Equation 3 above ignores cable losses. However, since these are very small and the same for both the sensor and reference cables (L_2 and L_5 in Figure 5) the effect is negligible.

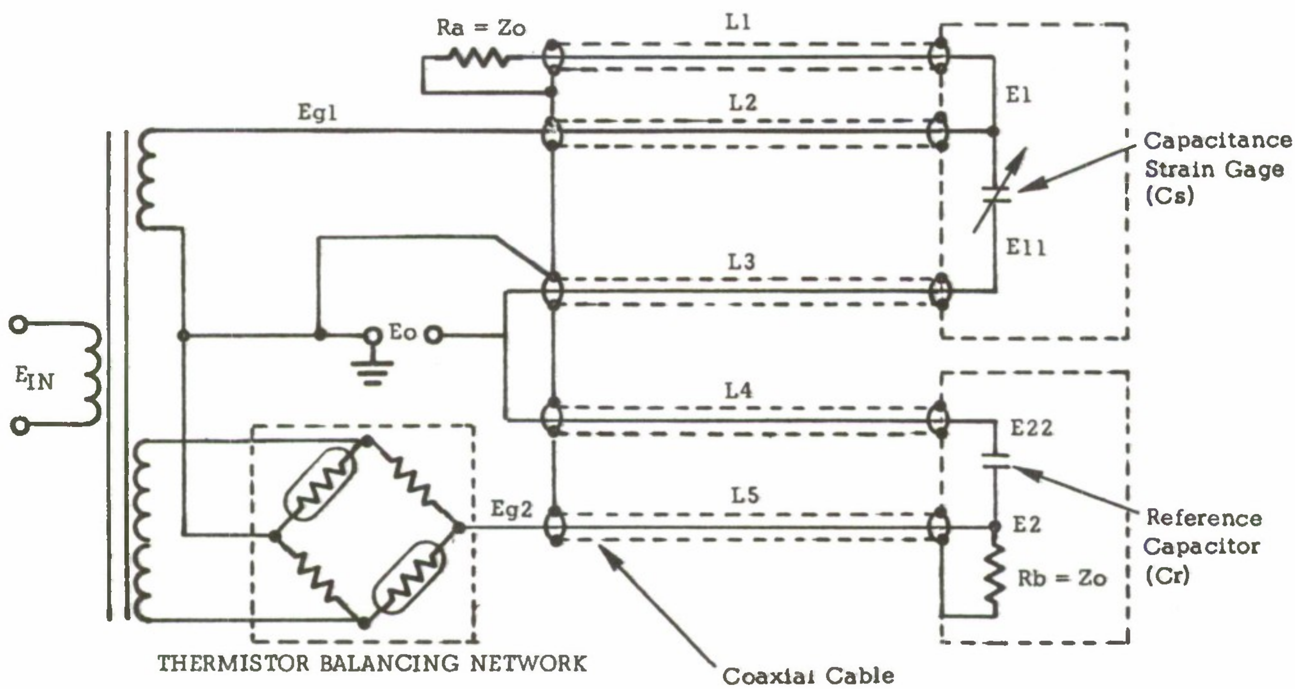


Figure 5. Basic Bridge

Table I below tabulates E_1/E_{g1} for various frequencies and cable lengths.

(2) If L_2 and L_5 are not terminated, the phase shift will be constant up to a cable length equal to 1/4 wavelength at which point the phase changes by 180°. However, the amplitude continuously changes and is quite sensitive to small changes in length, the temperature of the dielectric used in the cable, particularily in the hot area, and various other factors. For example, at odd 1/4 wavelengths the amplitude rises to a very large peak and is zero at each 1/2 wavelength. It was elected, therefore, to terminate the cable in its characteristic impedance and compensate for the phase shift by using an identical length of cable (L_5) to connect the reference capacitor into the bridge. This cable is also terminated in its characteristic impedance.

Since the capacitance strain gage operates at elevated temperatures, it is not practical to terminate the cable (L_2) at the strain gage with its characteristic impedance. Consequently, a matching section (L_1) terminated in the correct impedance by a resistor at the cold end is used to correctly terminate L_2. (See Figure 5)

TABLE I. SENSOR SIGNAL VS INPUT FREQUENCY FOR TWO CABLE LENGTHS

Frequency (Hz)	Cable Length (feet)	E_1/E_{g1} Magnitude	Phase (degrees)
1,000	150	Unity	-.09
10,000	150	Unity	-.90
100,000	150	Unity	-9.02
300,000	150	Unity	-27.10
500,000	150	Unity	-45.10
700,000	150	Unity	-63.10
1,000,000	150	Unity	-90.20
1,000	50	Unity	-.03
10,000	50	Unity	-.30
100,000	50	Unity	-3.01
300,000	50	Unity	-9.02
500,000	50	Unity	-15.00
700,000	50	Unity	-21.00
1,000,000	50	Unity	-30.10

(3) At the higher frequenices there are small error voltages (E_{11} & E_{22}) which are due to the sensor and reference capacitance currents flowing in the cables L_3 and L_4. At 1 MHz the series impedance of these cables in quite significant. These error voltages (E_{11} & E_{22}) are calculated from the following equation.

$$E_{11} = j\,\omega\, C_s\, E_1\, Z_o \tanh 2\sqrt{ZY}\cdot L \qquad (4)$$

where $j = \sqrt{-1}$

$\omega = 2\pi$ x frequency

C_s = capacitance of strain gage (farads)

E_1 = (See Figure 5)

Z_o = characteristic impedance of cable

= 53 ohms (typical)

Z = series inductance per unit length

= $.093 \times 10^{-6}$ henries/foot (typical)

Y = shunt capacitance per unit length

= 30×10^{-12} farads/foot

= 30 picofarads/foot (typical)

L = length of cable (feet)

This equation makes the following assumptions:
(1) the cable losses are negligible
(2) E_o = zero; i.e., bridge is balanced
(3) the gage capacitor has negligible losses

It can be shown that the actual value of the error signal E_{11} is modified only slightly by the presence of cable and gage losses.

Table II shows the magnitude and phase of E_{11} for the various conditions listed. The error signal E_{22} will, of course, follow the same pattern.

As can be seen, the error signal (E_{11}) rises to an alarmingly large value when the cable length reaches 1/4 wavelength; i.e., at a frequency of .99775 MHz for a 150 foot length of cable. This, of course, is due to the fact that a 1/4 wave line behaves as a resonant circuit. For a 50 foot cable and a strain gage capacitance of 30 pf, the error signal is 6.1×10^{-3} at 1 megahertz. This error signal is largely compensated for by an equivalent error signal occurring along the length of the coaxial cable (L_4) which connects the reference capacitor to the detector point.

TABLE II. ERROR DUE TO CABLE CURRENT FLOW

Line Length (feet)	Frequency (MHz)	Gage Cap. (pf)	Error E_{11}/E_1	
			Magnitude	Phase
150	.01000	30	.0000017	180°
	.10000	30	.0001700	180°
	.30000	30	.0016000	180°
	.50000	30	.0053000	180°
	.70000	30	.0145000	180°
	.80000	30	.0261000	180°
	.90000	30	.0610000	180°
	1.00000	30	3.0400000	0°
	1.10000	30	.0710000	180°
	.99000	30	.8450000	180°
	.99500	30	2.3600000	180°
	.99700	30	8.2300000	180°
	.99800	30	34.5000000	0°
	.99750	30	21.6000000	180°
	.99775	30	116.2000000	180°
150	.01000	10	.0000006	180°
	.10000	10	.0000550	180°
	.30000	10	.0005400	180°
	.50000	10	.0018000	180°
	1.00000	10	1.0100000	0°
	.99775	10	38.7000000	180°
50	.30000	30	.0005000	180°
	.50000	30	.0014000	180°
	1.00000	30	.0061000	180°
	2.00000	30	.0370000	180°
	3.00000	30	9.1000000	0°
	2.99325	30	3.5000000	180°
50	.50000	10	.0004700	180°
	1.00000	10	.0020000	180°

The thermistor balancing network shown in Figure 5 utilized a full bridge for operation. Later in the development stage it was determined that it was possible to use another configuration for balancing and the new configuration was chosen for the final design. Figure 6 shows the final capacitance balance network in conjunction with a balance amplifier and a thermistor. The resistance of the thermistor is sensed, using a D. C. voltage, to yield the D. C. analog to capacitance.

Referring to Figure 6, the circuit works in the following manner. Assume the oscillator has an output E_3 which can be increased or decreased depending on the amplitude and phase of an amplified error signal i.e., if we let one of the capacitors vary, then the error signal varies and the oscillator output changes. If it increases, the current into the thermistor increases, increasing its power dissipation and lowering its resistance which in turn changes the voltage E_b' in such a direction to bring the error back to zero.

We can say that, since i_e must be zero, that

$$i_s = i_R = E_b j\omega C_s = E_b' j\omega C_R \tag{5}$$

and if we assume that the impedance of C_R is very high with respect to R_P then:

$$E_b' = \frac{E_b\ (R_{TH} - R_1)}{R_{TH}\ (1 + R_1/R_3 + R_1/R_P) + R_1} \tag{6}$$

Combining these equations we find that

$$\frac{C_s}{C_r} = \frac{(R_{TH} - R_1)}{R_{TH}\ (1 + R_1/R_3 + R_1/R_P) + R_1} \tag{7}$$

This equation defines the relationship of the thermistor resistance and the reference and sensor capacitance.

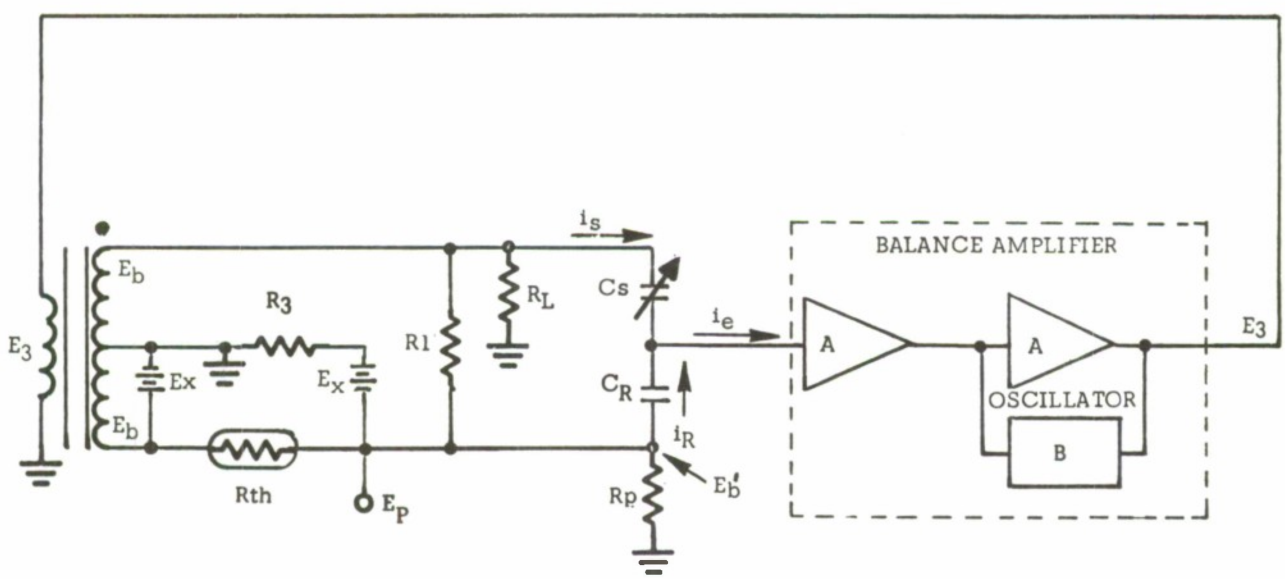


Figure 6. Simplified Schematic, Automatic Capacitance Balance Network

b. D. C. Operation

Figure 7 is the D. C. equivalent circuit of the automatic capacitance balance circuit.

It can be shown that

$$E_p = \frac{E_x \; (R_1 - R_{TH})}{R_{TH} \; (1 + R_3/R_p + R_3/R_1) + R_3} \qquad (8)$$

This equation defines the relationship of the thermistor resistance and the D. C. analog output voltage.

The A. C. equation (7) and the D. C. equation (8) can be simplified to (9) if $R_1 = R_3$

$$E_p = -E_x \frac{C_s}{C_R} \qquad (9)$$

These equations are valid only if the AC and DC impedances remain identical for all resistors and the leakages are small with respect to intended values. When these assumptions are met then it can be seen that a DC voltage, E_p, is proportional to the ratio of two capacitors.

The D. C. voltages are generated by a precision voltage source as shown in Figure 8.

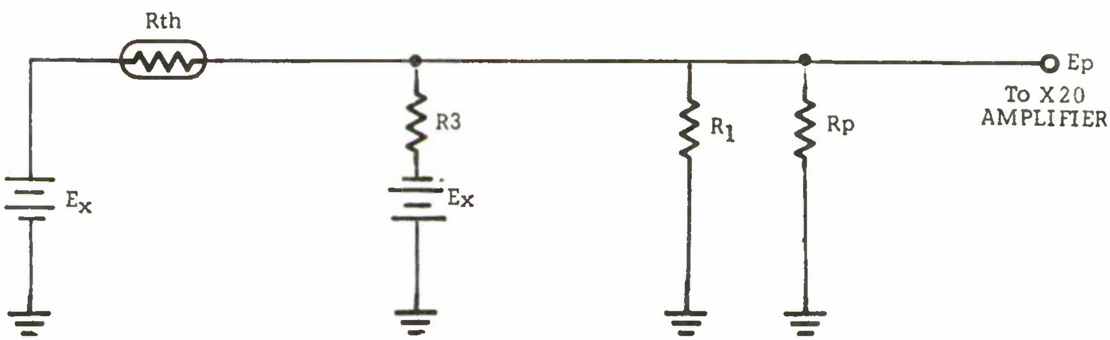


Figure 7. D. C. Equivalent Circuit, Automatic Capacitance Balance Network

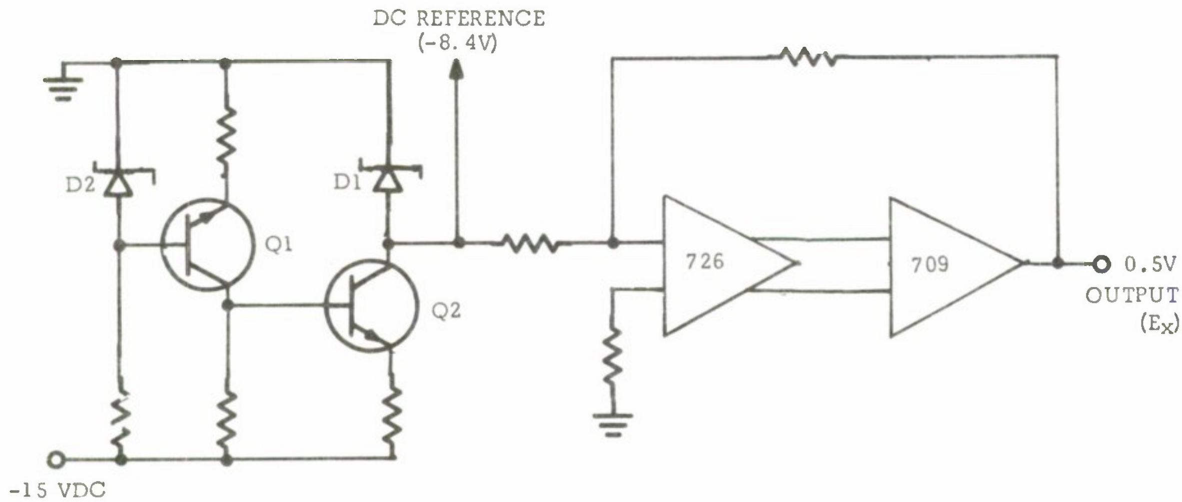


Figure 8. Simplified Schematic, 0. 5 Volt Power Supplies

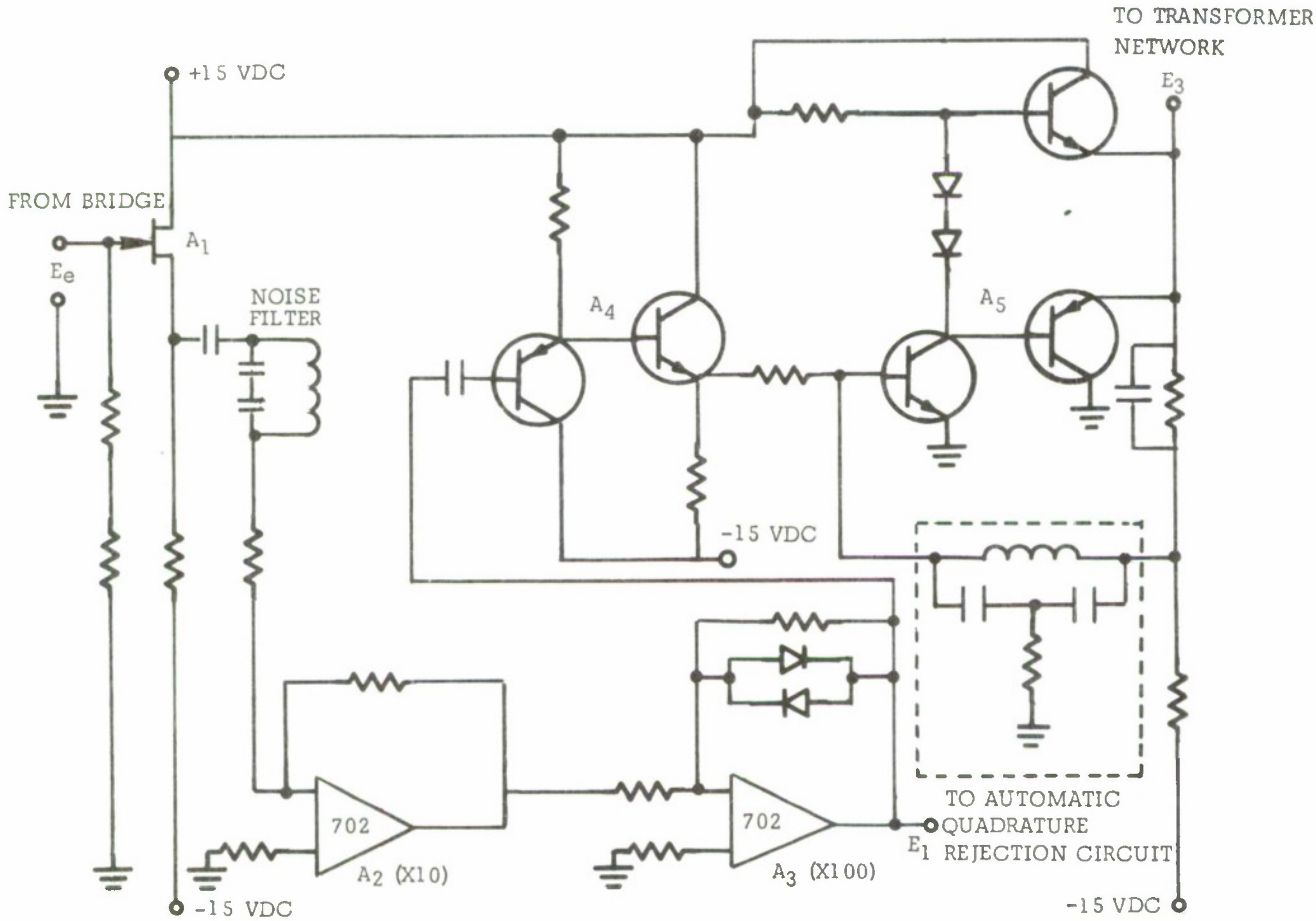


Figure 9. Simplified Schematic Balance Amplifier

The power supply is a precision dc amplifier having a gain of considerably less than unity, which amplifies a dc reference voltage derived from a zener diode (D1) which in turn is supplied from a constant source consisting of another zener diode (D2) and transistors QI and Q2. This amplifier consists of a linear integrated circuit amplifier (709) and an integrated circuit preamplifier (726) which is a matched pair of transistors and a temperature control circuit on a single chip. The temperature control circuit maintains the chip at a constant temperature, resulting in a dc amplifier having a zero drift of less than ±50 microvolts over a temperature range of 0° to 40°C. The output impedance of this circuit is extremely low (typically less than 1 milliohm). The -0.5 volt power supply is essentially the same design.

Wherein certain components of this circuit are unusual, they are fully described in another section.

5. Balance Amplifier

The amplifier used in the automatic capacitance balance circuit (See Figure 6) is the balance amplifier. It is shown in more detail in Figure 9.

As can be seen it consists of a field effect transistor as an input source follower to attain a very high input impedance. The source follower is proceeded by a pi-section filter to reduce noise and limit the response for high frequency stability. The filter is followed by two stages of 702 amplifiers, the first with a gain of 10, the second has a gain of 100. The output of this stage of amplification is used to drive the automatic quadrature rejection circuit. The signal is the amplified error signal.

The second 702 amplifier has a double emitter follower for buffering and then supplies the error signal to a tuned amplifier. The tuned amplifier uses a L-C bridged-T network as the feedback element.

To attain various operating frequencies, the bridged-T networks are switched into the feedback network using reed relays controlled by a switch on the remote unit panel.

The use of the bridged-T network in a feedback amplifier is explained in detail in the literature.[1]

6. Automatic Quadrature Rejection Circuit

If the sensor capacitor has a high loss angle, error signal ie (Figure 6) at the input to the amplifier will contain a quadrature component. This will mean that if oscillation is to continue, the frequency of oscillation will tend to change by an amount such that the change in the phase shift of the tuned circuit just

---

[1] Valley and Wallman, Vacuum Tube Amplifier, McGraw Hill 1948 pp 284-408.

offsets the phase shift induced in i_e by the presence of the quadrature signal. This change in phase shift can be used as a means of detecting the amount of quadrature signal. To balance the quadrature signal due to the loss angle of the sensor, a quadrature signal is fed to the bridge balance point through an electronically variable resistor from a voltage in phase with the reference signal. This electronically variable resistor is a photo conductive cell which is illuminated by a lamp mounted in the same housing as the photo cell (Figure 17). The current through the lamp is controlled so that the resistance of the photo cell exactly compensates for the loss resistance in the sensor capacitor. The current through the lamp is a dc signal which is obtained from a passive phase shifting network, driven from windings on the bridge transformer.

Figure 10 shows the details of the circuit which detects the phase difference between the input and the output of a tuned amplifier which has output E3 and input E1. The phase shift between E1 and E3 is exactly 180° in the absence of a quadrature error signal. In the presence of a large quadrature error signal (i_e) at the input amplifier there will be a significant phase shift between E3 and E1. E1 is then applied through emitter follower amplifier to the phase sensing detector. The phase between point X and point Y, and between point X and point Z in Figure 10 will be shifted exactly 90° when equation (10) shown below is satisfied. Consequently, the voltage at point Y (E4) is the vector sum of E2 and the +90° reference signal Er. Similarly, E5, the voltage of point Z, is the sum of E2 and the -90° reference signal Er'.

$$R_1 C_1 = R_2 C_2 = \frac{1}{2\pi f} \tag{10}$$

where $2\pi f$ = radian frequency

and the values for R1, R2, C1, and C2 are as shown in Figure 10.

The amplitude and phase of these various voltages is shown in Figure 11, and 12. Figure 11 shows the phase and amplitude relationships when E2 is in phase with the bridge voltage E3. In other words, it is shifted exactly 90° with respect to Er and Er'. In this case, the resultant voltages E4 and E5 will be exactly equal, but will not be in phase. These two voltages are individually rectified by means of diodes D1 and D2, resulting in dc voltages across resistors R3 and R4 which are equal. Figure 12 demonstrates the phase and amplitude relationships when E2 is not in phase with the bridge input. It can be seen that E4 and E5 will not be equal in amplitude under these conditions. This results in the rectified dc voltages across R3 and R4 being unequal, providing a dc input to the dc amplifiers A7 and A8. This, in turn, causes a current to flow through the lamp which illuminates the photocell, reducing the resistance of the photocell in such a way so as to reduce the quadrature signal which initially caused the phase shift between E2 and the bridge voltage E3.

Figure 13 shows the circuits of the entire capacitance measuring system.

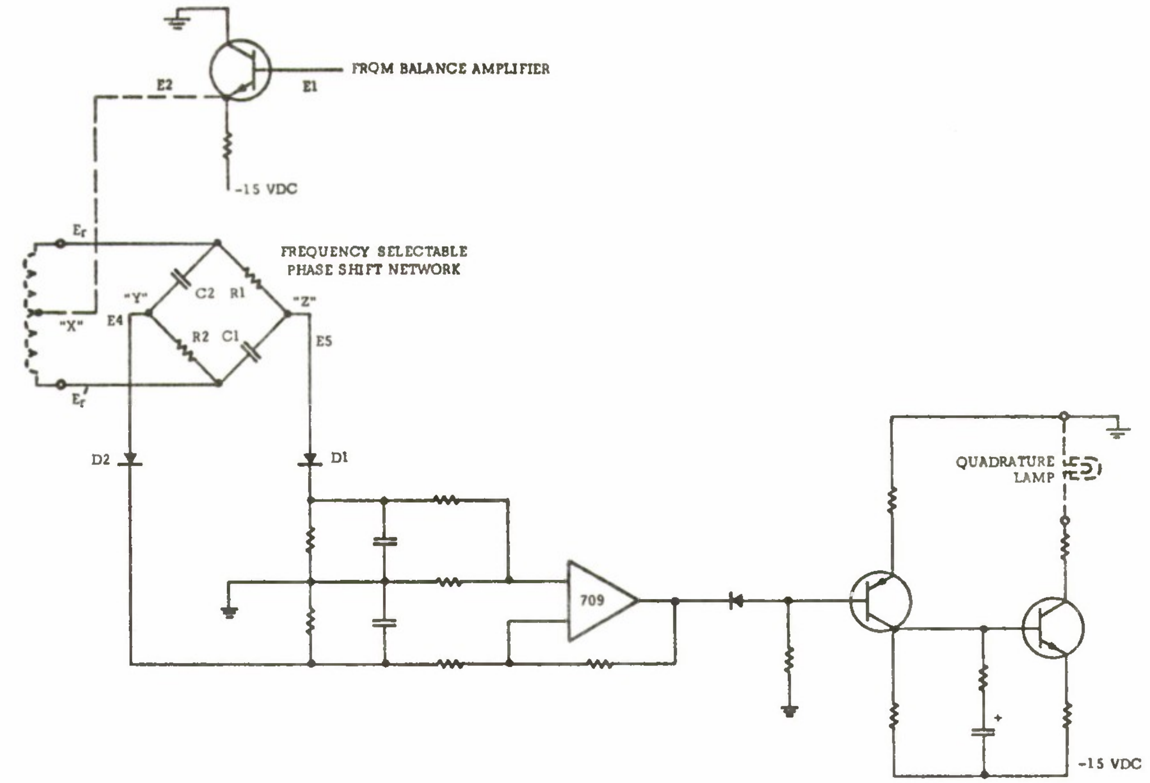


Figure 10. Simplified Schematic Automatic Quadrature Rejection Circuit

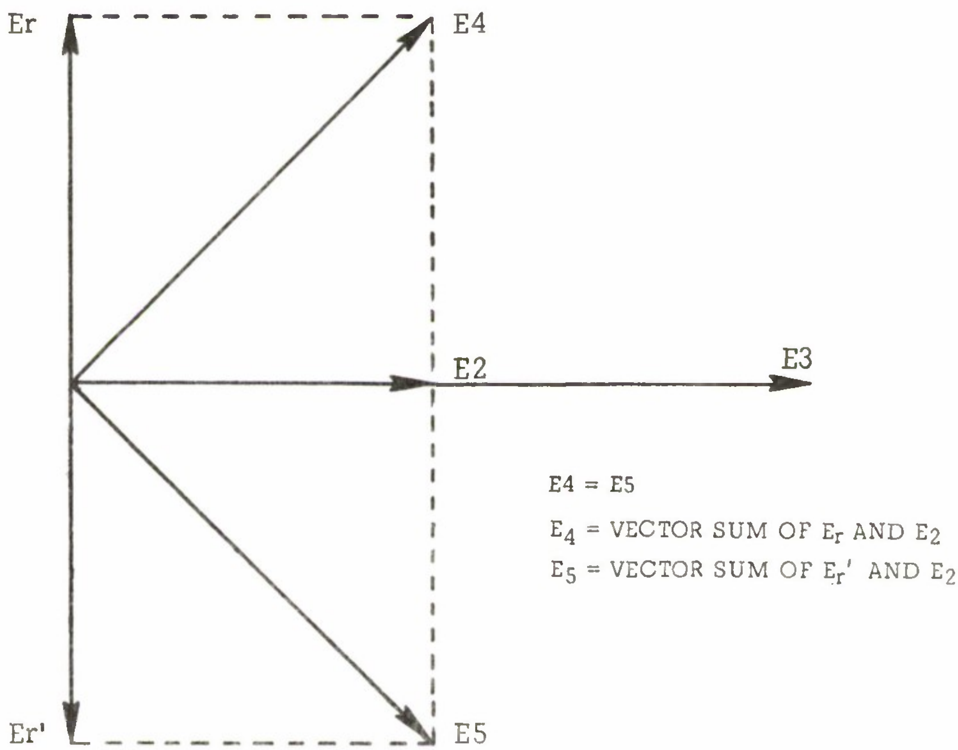


Figure 11. Phase and Amplitude Relationships When E2 Is In Phase With Bridge Input (When there is no quadrature)

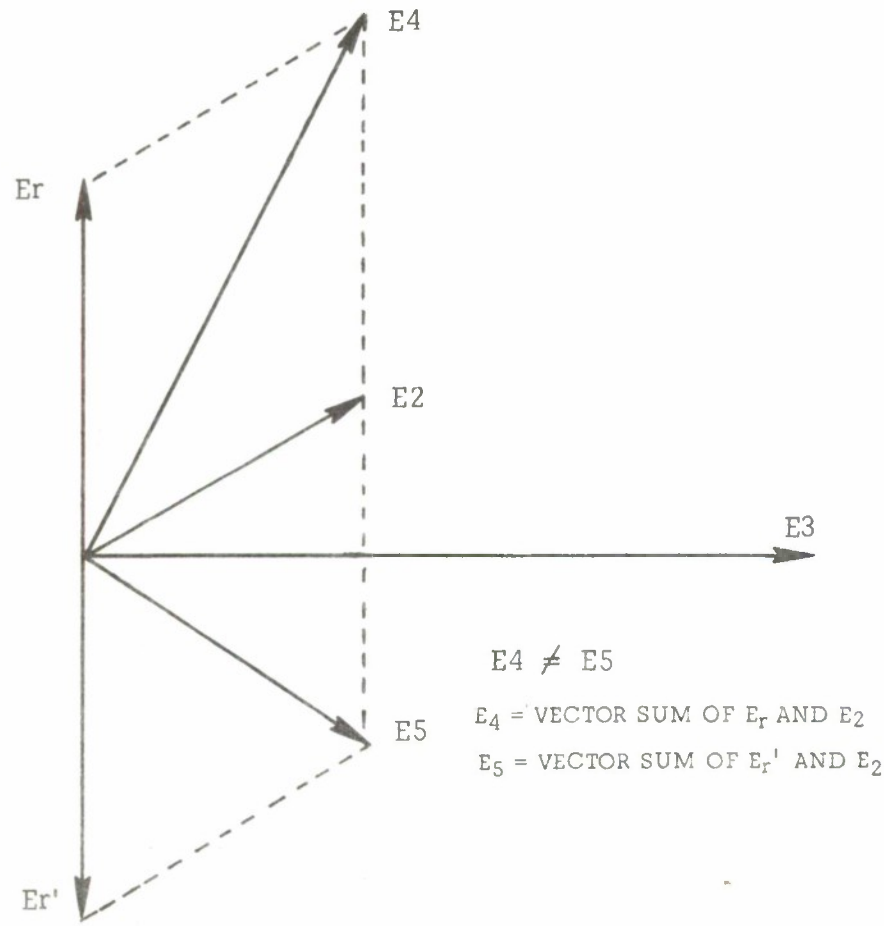


Figure 12. Phase and Amplitude Relationships When E2 Is Not In Phase With Bridge Input (When there is quadrature)

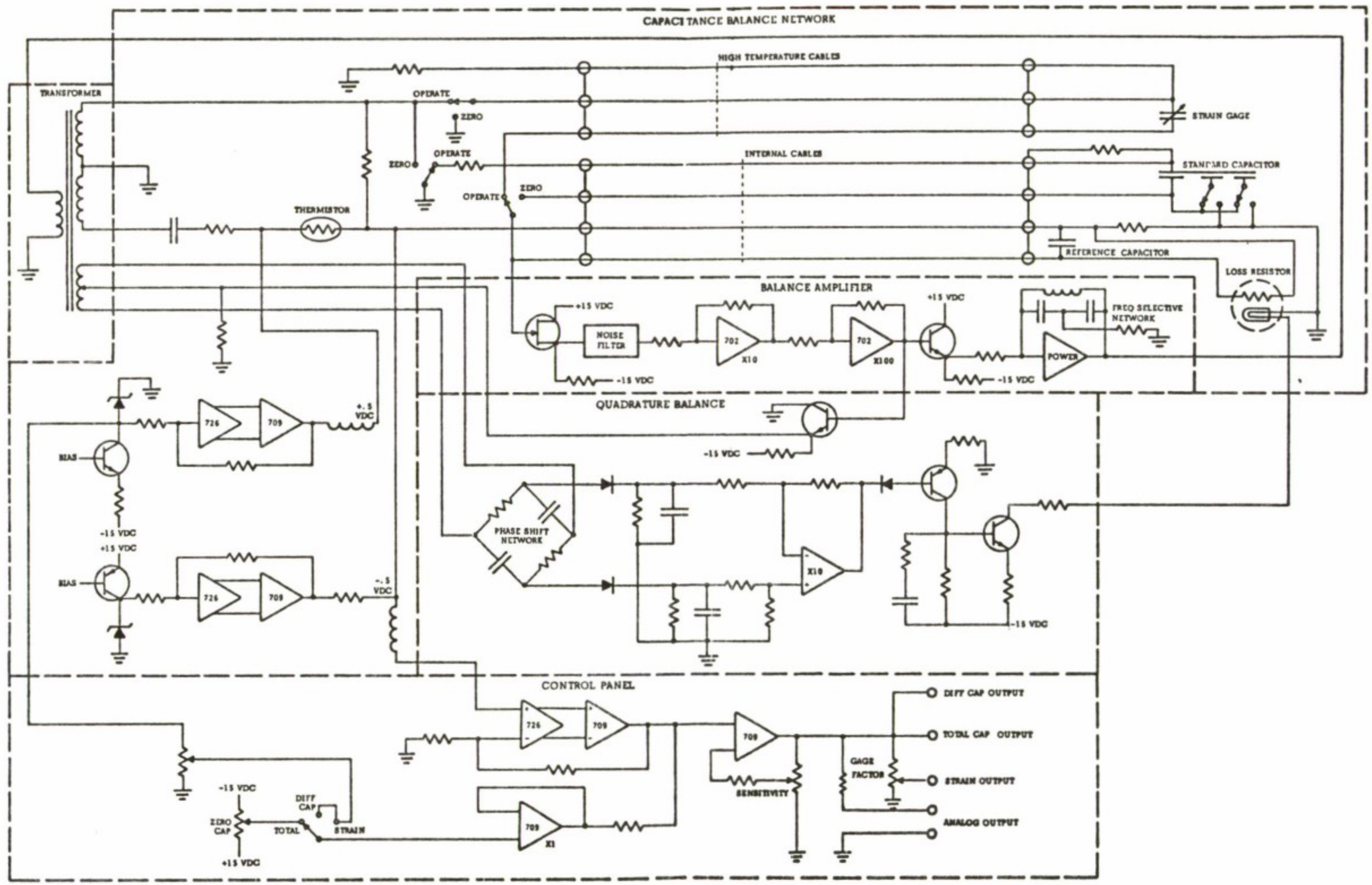


Figure 13. Automatic Capacitance Measuring System Simplified Schematic Diagram

SECTION IV

DEVELOPMENT DIFFICULTIES

1. Introduction

This section discusses problems encountered during development of the automatic capacitance measurement system. The problems discussed are those which presented insurmountable difficulties insofar as meeting target specifications.

2. 1 MHz Operation

The most difficult and elusive problem encountered during development of the automatic capacitance measuring system was that of attempting to establish operation at 1MHz. Basically the problem was established as being one of maintaining a system with an adequate phase margin to be stable, without undesired oscillation, and remaining so at all frequencies.

The establishment of a stable system was accomplished using the internal standard capacitor. This was implemented by adding a phase lead circuit in the tuned output stage. The system did not oscillate at any unwanted frequencies but was only marginally stable. Any attempts to further reduce bandwidths of the amplifiers to achieve a more stable system brought the loop gain so low as to give a sluggish and sometimes unresponsive system.

When the external capacitance was connected, the difference in phase shift immediately made the system unstable. Manually adjusting the terminations made the system marginally stable again. However the output was very inaccurate due to small changes in the velocity of propagation between the two summing junction cables, and when the loss resistor was added the system again required phase adjustment to alleviate oscillation. It was also revealed that the components inserted to correct phase at 1MHz adversely affected operation at lower frequencies. It was obvious after these investigations that the system could not be made fully automatic for the lengths of cable required and with the unknown changes that would occur in the cables under actual useage. It was at this point that it was requested that the 1MHz requirement be removed from the contract.

3. Quadrature Error

During tests conducted on the unit it was found that a small error was introduced when the loss component was added. This is surmised to be due to the photocell technique used for quadrature balance. The photocell is a device based on the freeing of electrons and thus is, by very definition of dielectrics and dielectric constant, susceptible to potentials causing a change in capacitance. Whereas the D. C. potential across the photocell changes as a function of sensor capacitance and the number of free charges is a function of the impinging light caused by the quadrature balance network the capacitance becomes a function of two variables. The inherent capacitance of the photocell was measured under no light conditions and was found to be .004 pf. Measurement under light conditions was attempted but found to be impossible with the low value of resistance across the cell.

The system error was found to be the inverse of the loss factor. Thus for a loss factor of 1 if the error is 1% and the loss factor then changed to 2 (twice the resistance) the error is 0.5% indicating a relationship between the conductivity and capacitance. The apparent error on the system output, which is a decrease in the total capacitance reading, also indicates an increase in capacitance across the reference capacitor as would be caused by the photocell.

4. High Temperature Cables

The high temperature cables proved difficult to obtain, and once installed in the system, were found to irritate the 1 MHz operational problem. The system operates in such a manner as to require equal impedances in both legs of the capacitance bridge. In the "standardize" mode of operation all signals are routed through internal cables while in the "operate" position the standard capacitor is connected through internal cables and the gage is measured through the high temperature cable. The impedances of the cables appear very nearly identical at low frequencies; however at 1 MHz the cables did not appear nearly so identical. This is due partly because the cables are of different materials and, even though designed identically, are not really so. In addition the internal cables are coiled giving rise to additional line inductance. Thus, this small difference in impedance aggravated the already unstable 1 MHz operation.

SECTION V

SPECIAL COMPONENTS

1. Introduction

This section contains details of the manufacture of special items peculiar to the development and manufacture of the automatic capacitance measuring system.

2. Reference and Standard Capacitors

The operation of the automatic capacitance measuring system requires two extremely stable capacitors. One is the reference capacitor which is used as one element in the capacitance balance network. The second is the standard capacitor which is used as an internal standard for calibrating the sensitivity of the measuring system.

The basic construction of both is identical. The capacitor is formed by platinizing both sides of a 1/16 inch quartz plate and then electro-scribing the areas to provide an accurate capacitance value. Quartz is the dielectric, and was chosen because of its inherent stability with respect to temperature and time.

Figure 14 and 15 show the dimensions of the capacitors. The standard capacitor has a basic capacitance of 18pf with two sections of 2pf each. These additional sections can be paralleled or grounded to provide 18, 20 or 22pf.

The reference capacitor has a basic capacitance of 50.0pf. The capacitors are mounted in metal cans to provide shielding as shown in Figure 16. The standard capacitor housing also provides room to mount two reed relays used to switch the 2pf capacitance in and out of the circuit.

3. Loss Resistor

The reference arm of the capacitance bridge contains a lamp-photocell combination used in parallel with the capacitor to provide the required loss component. The requirements for the photocell are high sensitivity and low capacitance as well as a very wide dynamic range. After evaluation it was found that the best combination was a Clairex photocell CL902 and a No. 80 lamp arranged as shown in Figure 17.

The combination measured only .004pf capacitance and had a range from 20M to 100K ohms with drive current from 7mA to 13.8mA lamp current.

4. Thermistor

The thermistor assembly is a thermistor (VEECO 3147 or Fenwal GC31L1) mounted in a HC-6/U crystal holder. Mounting the thermistor in the holder provides mechanical protection for the thermistor, which is about the size of a pin head, and also tends to stabilize its environment, offering additional stability.

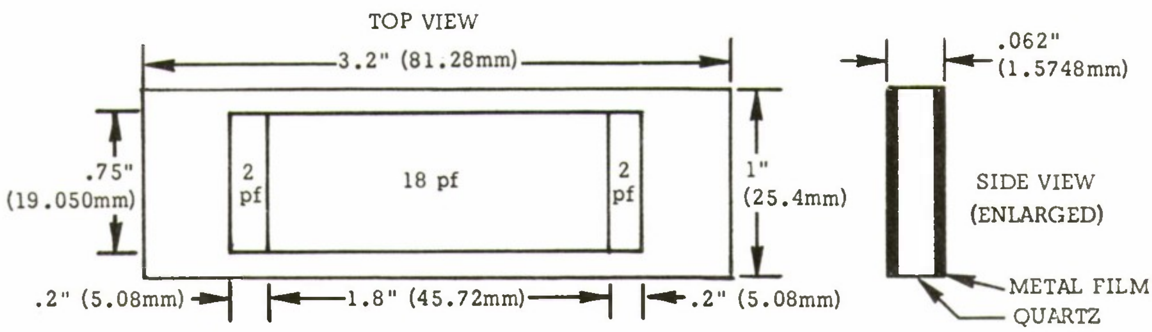


Figure 14. Dimensions of Standard Capacitor

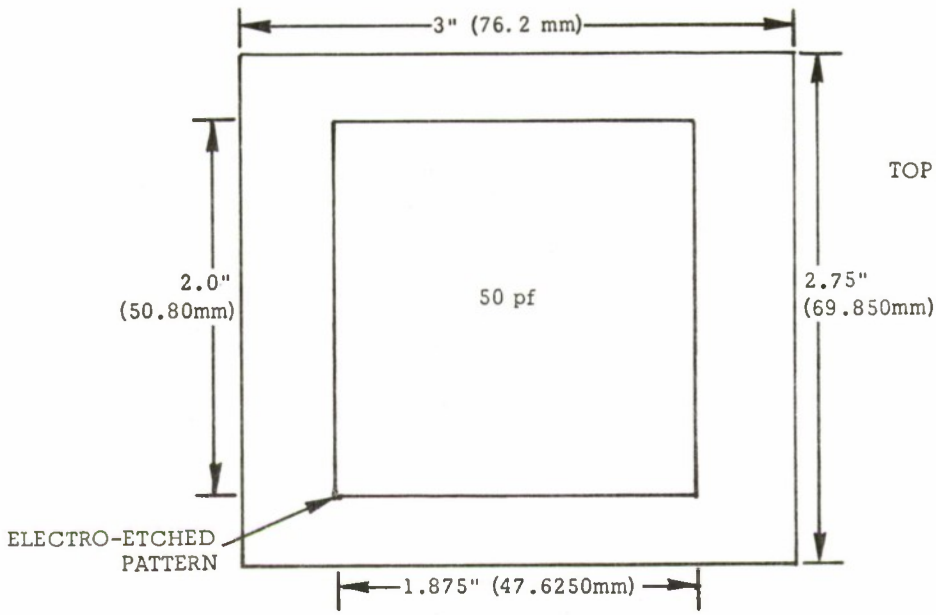


Figure 15. Dimensions of Reference Capacitor

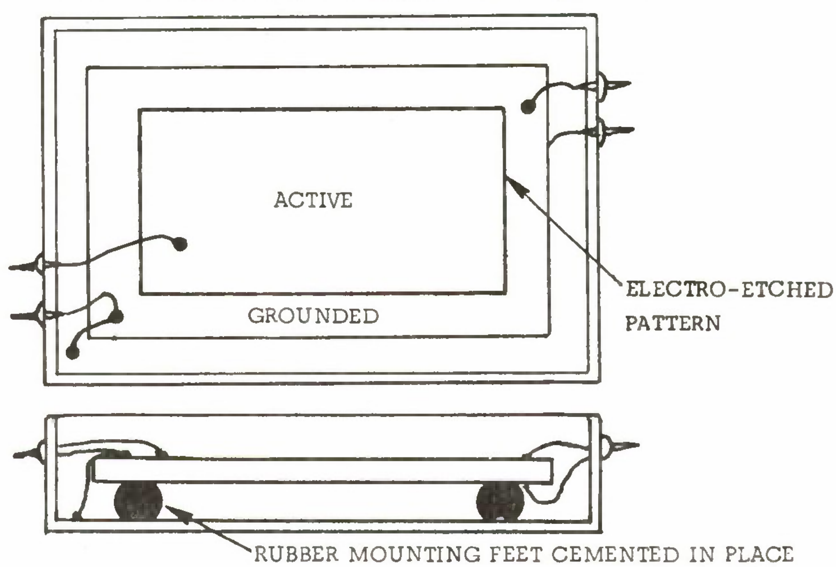


Figure 16. Standard and Reference Capacitor Mounting Details

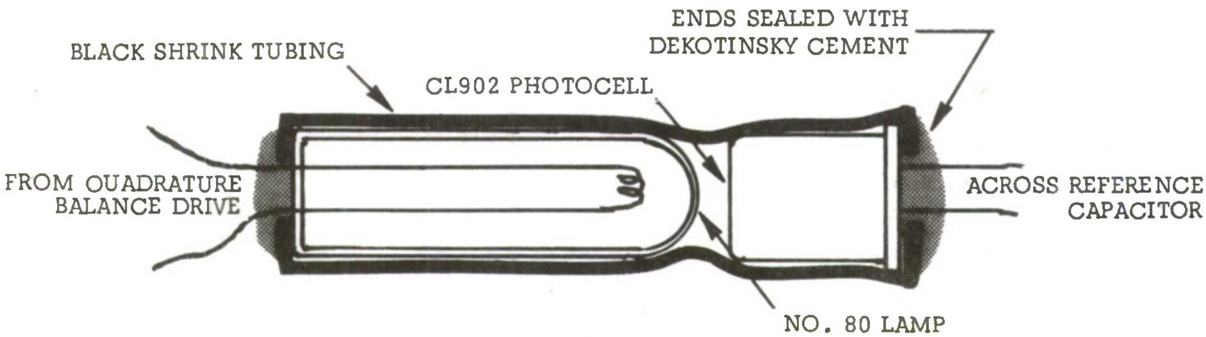


Figure 17. Loss Resistor Assembly Details

5. Transformers

The two transformers that are used in the bridge circuit are manufactured on ferrite toroids. The transformers are closely coupled with the winding techniques consistent with the manufacture of closely coupled transformers.

One transformer is used at 1 KHz, 5 KHz and 30 KHz. This transformer is wound using 24 gauge wire (heavy formvar). The primary is 50 turns, two secondaries are 50 turns each and the remaining secondaries are 30 turns each. The core was a Ferroxcube part no. 400T750/3E ferrite toroid. Mylar tape is used between overlapping windings and over the exterior surface of the completed transformer.

The second toroid is used at 150 KHz. The transformer is wound with a 5 turn primary, two secondaries with 5 turns each and the two remaining secondaries have 3 turns each. The two pairs of secondaries are wound bifilar to equate the capacitance and leakage inductance parameters. These transformers are wound using 22 gauge wire (heavy formvar). The core used for these transformers is a Ferroxcube part no. K300502. Mylar tape was used to separate the primary and the secondaries. The primary is wound by equally spacing the turns around the circumference of the toroid.

SECTION VI

TEST PLAN

This section contains the test plan which was used to establish if the system was operating properly.

AUTOMATIC CAPACITANCE MEASURING SYSTEM TEST PLAN

The following test plan describes a series of tests performed on an automatic capacitance measuring system designed for use with capacitance strain gages. This equipment was developed and fabricated under contract number F33615-69-C1298 for the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base. The test plan was designed to determine whether or not the equipment performs to the contract specifications. The main performance specifications are listed below:

(a) initial gage capacitance: 10 to 30 pf

(b) gage capacitance change: ±2 pf

(c) maximum rate of change of capacitance: ±.2 pf/second

(d) accuracy: ±.1%

(e) resolution: ±0.002 pf

(f) output: 50 millivolts d.c. per picofarad

(g) drift: ±250 microvolts per hour (±.005 pf/hour)

(h) linearity: ±0.1%

(i) operating frequencies: 1000, 5,000, 30,000, and 150,000 Hz.

Test Equipment

The equipment under test was essentially a capacitance bridge, and consequently, its performance was determined by comparing its reading against the capacitance of variable precision air capacitors whose value, in turn, was determined by means of a standard capacitance bridge. Consequently, the test circuit shown in Figure 18 is a capacitance bridge wherein the variable capacitance consisting of CV_1 and CV_2 in parallel is used to simulate the strain gage and is precisely compared with a 100 pf air standard in the standard bridge using the precision ratio transformers T_1 and T_2.

T_1 is a 1:1 ratio transformer designed for optimum performance at 1kHz. T_2 is a decade ratio transformer Model DT72A manufactured by Electro Scientific Instruments Inc. This transformer has guaranteed ratio accuracies of better than 1 ppm and has an NBS traceable calibration certificate. The

100 pf standard air capacitor (C_S) was a Type 1404 three-terminal capacitor manufactured by the General Radio Company. This capacitor has an initial adjustment accuracy of ±5 ppm and a stability of ±20 ppm per year. This reference capacitor also has an NBS traceable calibration certificate.

CV_1 was a General Radio Type 1422-CC precision variable air capacitor having a range of 5 to 110 pf and a scale factor of 0.02 pf per scale division. This capacitor was used to simulate the initial capacitance of the strain gage (10 to 30 pf). CV_2 was a General Radio Type 1422-CD precision variable air capacitor having two ranges. These ranges are 0.5 to 11 pf and 0.05 to 1.1 pf and scale factors of 0.002 pf per division and 0.0002 pf per division respectively. CV_2 was used on the high range to simulate the change in gage capacitance with strain.

Loss Angle Simulation

Since the strain gages that will be used with this system have very high dielectric losses at high temperatures, it was necessary to simulate these high losses in order to determine that the equipment maintained accurate performance at high gage temperatures. Consequently, a means for inserting fixed metal film resistors in parallel with the variable capacitor was provided. As can be seen, these fixed resistors were only in parallel with the variable capacitor when the variable capacitors are connected to the capacitance measuring system under test. No provision was made for accurately measuring the value of these resistors since no measurement of loss angle was intended. However, these resistors had values known to within ±5%, consequently permitting calculation of the loss angle to this accuracy.

Test Procedure

Table III lists a sequence of tests, 1 through 9, which were conducted to determine the basic accuracy and linearity at 1000 hertz.

Test I was an adjustment procedure.

Tests 2 through 9 required that the true value of the sum of CV_1 and CV_2 be determined by disconnecting these capacitors from the system under test and connecting them into the standard capacitance bridge (see Figure 18) and adjusting CV_1 and CV_2 until the desired values of capacitance was obtained. The capacitors were then reconnected into the system under test and the sequence listed in Table III continued. The value of CV_1 and CV_2 were recorded and listed in Table IV.

During all tests a total of 150 feet of cable was used between CV_1, CV_2, and the control panel for the system under test. This included 100 feet of cable to the "remote" unit and 50 feet of high temperature coaxial cable to CV_1 and CV_2.

Tests 10, 11, 12, & 13 - same as Test 1, 2, 8, & 9, except CV_1 was set to 15.000 pf.

TABLE III. SYSTEM VERIFICATION TEST SETTINGS (PARTIAL)

Test No.	Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	Sensor Simulate (pf) CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	Ideal DVM Reading	Spec Error ($V\times10^{-3}$)
1	1	1	-	-	CT	Zero	Zero	-	0.000	
	2		-	-	CT	18pf STD	Sensitivity	-	+1.800	
	3		-	-	CT	20pf		-	+2.000	±3
	4		-	-	CT	22pf		-	+2.200	±3
	5		-	-	ΔC	22pf	Dif. Adj.	-	0.000	
	6		-	-	ΔC	20pf		-	-0.200	±3
2	1		5.000	5.000	CT	Operate		-	+1.000	±3
	2		5.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	±3
	3		5.000	4.500	CT	Operate		-	+0.950	±3
	4		5.000	4.500	ΔC	Operate		-	-0.050	±3
3	1		5.000	5.500	CT	Operate		-	+1.050	±3
	2		5.000	5.500	ΔC	Operate		-	+0.050	±3
4	1		5.000	4.000	CT	Operate		-	+0.900	±3
	2		5.000	4.000	ΔC	Operate		-	-0.100	±3
5	1		5.000	6.000	CT	Operate		-	+1.100	±3
	2		5.000	6.000	ΔC	Operate		-	+0.100	±3
6	1		5.000	3.500	CT	Operate		-	+0.850	±3
	2		5.000	3.500	ΔC	Operate		-	-0.150	±3
7	1		5.000	6.500	CT	Operate		-	+1.150	±3
	2		5.000	6.500	ΔC	Operate		-	+0.150	±3
8	1		5.000	3.000	CT	Operate		-	+0.800	±3
	2		5.000	3.000	ΔC	Operate		-	-0.200	±3
9	1		5.000	7.000	CT	Operate		-	+1.200	±3
	2		5.000	7.000	ΔC	Operate		-	+0.200	±3

b) CT represents "Total Capacitance;" ΔC represents "Differential Capacitance."

TABLE IV. CALIBRATION DATA FOR GENERAL RADIO PRECISION CAPACITORS

Part No. 1422 CD, S/N 4882				Part No. 1422 CC, S/N 5748	
Measured Capacitance (pf)	Dial Setting (pf)	Measured Capacitance (pf)	Dial Setting (pf)	Measured Capacitance (pf)	Dial Setting (pf)
3.000	2.995	5.500	5.491	5.000	5.26
3.500	3.492	6.000	5.991	10.000	10.20
4.000	3.991	6.500	6.493	15.000	15.16
4.500	4.491	7.000	6.994	20.000	20.13
5.000	4.991			25.000	25.10

Test 14, 15, 16, & 17 - same as Test 1, 2, 8, & 9, except CV_1 was equal to 25.000 pf.

Tests 18, 19, 20, & 21 - same as Tests 14, 15, 16, & 17, except the loss resistor (R_L) was equal to 5 megohm. (Note: a loss resistor of 5 megohms is equivalent to a loss angle of approximately unity for $CV_1 + CV_2 = 30$ pf at a frequency of 1 kHz.)

Tests 22 through 25 - same as Tests 14 through 17, except the frequency was equal to 5 kHz.

Tests 25 through 28 - same as Tests 22 through 25, except $R_L = 1$ megohm. (Note: a loss resistance of 1 megohm is equivalent to a loss angle of approximately unity for $CV_1 + CV_2 = 30$ pf at a frequency of 5 kHz.)

Tests 29 through 32 - same as Tests 14 through 17, except the frequency was 30 kHz.

Tests 33 through 36 - same as Tests 29 through 32, except the loss resistor was equal to .15 megohms.

Tests 37 through 40 - same as Tests 14 through 17, except the frequency was equal to 150 kHz.

Tests 41 through 44 - same as Tests 37 through 40, except the loss resistor was equal to 33,000 ohms.

Tests 45 through 48 - intentionally omitted. (Note: Throughout the procedure certain tests were omitted since they were originally intended at 1 MHz.)

Tests 49 through 52 - intentionally omitted.

Test 53 - Determination of resolution - same as Test 2, except CV_2 was set to 5.005 for Steps 3 and 4, instead of 4.500. The digital voltmeter reading from Step 1 to Step 3 and from Step 2 to Step 4 should have increased by .0005 ±.0002.

Test 54 - same as Test 53, except the frequency was equal to 5 kHz.

Test 55 - same as Test 53, except the frequency was equal to 30 kHz.

Test 56 - same as Test 53, except the frequency was equal to 150 kHz.

Test 57 - intentionally omitted.

Test 58 - Determination of the effect of ambient temperature.

Step 1: The complete system was placed in an environmental oven at 25°C.

Step 2: "Standardize" Bridge as in Test 1 and perform Test 9. Digital voltmeter readings were noted.

Step 3: The temperature was increased to 40°C and steps 1 and 2 were repeated. Digital voltmeter readings were noted.

Step 4: Temperature was decreased to 10°C and Steps 1 and 2 were repeated. Digital voltmeter readings were noted.

The voltmeter readings in all cases should have been within the tolerances indicated in Table III.

Test 59 - Determination of response time.

This test required an auxiliary capacitor of approximately .2 pf and a two-pole switch to connect this capacitor in parallel with CV_1 and CV_2 or disconnect it from the circuit.

Step 1 & 2: The bridge was standardized as in Test 1, Steps 1 and 2

Step 3: CV_1 and CV_2 were each set to 5.000 pf

Step 4: The .2 pf capacitor was switched in parallel with CV_1 and CV_2 and the reading of the digital voltmeter was noted.

Step 5: The .2 pf capacitor was switched out of circuit and whether the digital voltmeter reading had returned to the previous reading within the specified accuracy within 1 second was noted. For this test, the sample rate of the digital voltmeter was set to a maximum, i.e. approximately 16 samples per second. (Note: the inherent response time of the electronics are typically .01 second and, consequently, the reading was completely stabilized well within 1 second.)

Step 6: The .2 pf capacitor was switched into circuit and whether the voltmeter reading had stabilized to the previous value within 1 second within the specified accuracy was noted.

Test 60 - same as Test 59, except CV_1 = 25 pf.

Test 61 - same as Test 59, except the frequency was equal to 150 kHz.

Test 62 - D.C. output voltage sensitivity.

Step 1: The bridge was standardized as in Test 1, Steps 1 & 2.

Step 2: CV_1 and CV_2 were each set to exactly 5.000 pf, i.e. a total of 10.00 pf.

Step 3: CV_2 was increased from 5.000 to 5.200 and the digital voltmeter reading was noted.

Test 63 - same as Test 62, except that CV_1 = 25 pf.

Test 64 - same as Test 62, except the frequency was 150 kHz.

Test 65 - Steps 1, 2, and 3 were the same as Test 62. Step 4 - the equipment was turned on for one hour and then the digital voltmeter reading was noted.

Test 66 - same as Test 65, except CV_1 = 25 pf.

Test 67 - same as Test 65, except the frequency was 150 kHz.

Test 68 - Linearity

Step 1: The digital voltmeter was connected to the external d.c. output terminals.

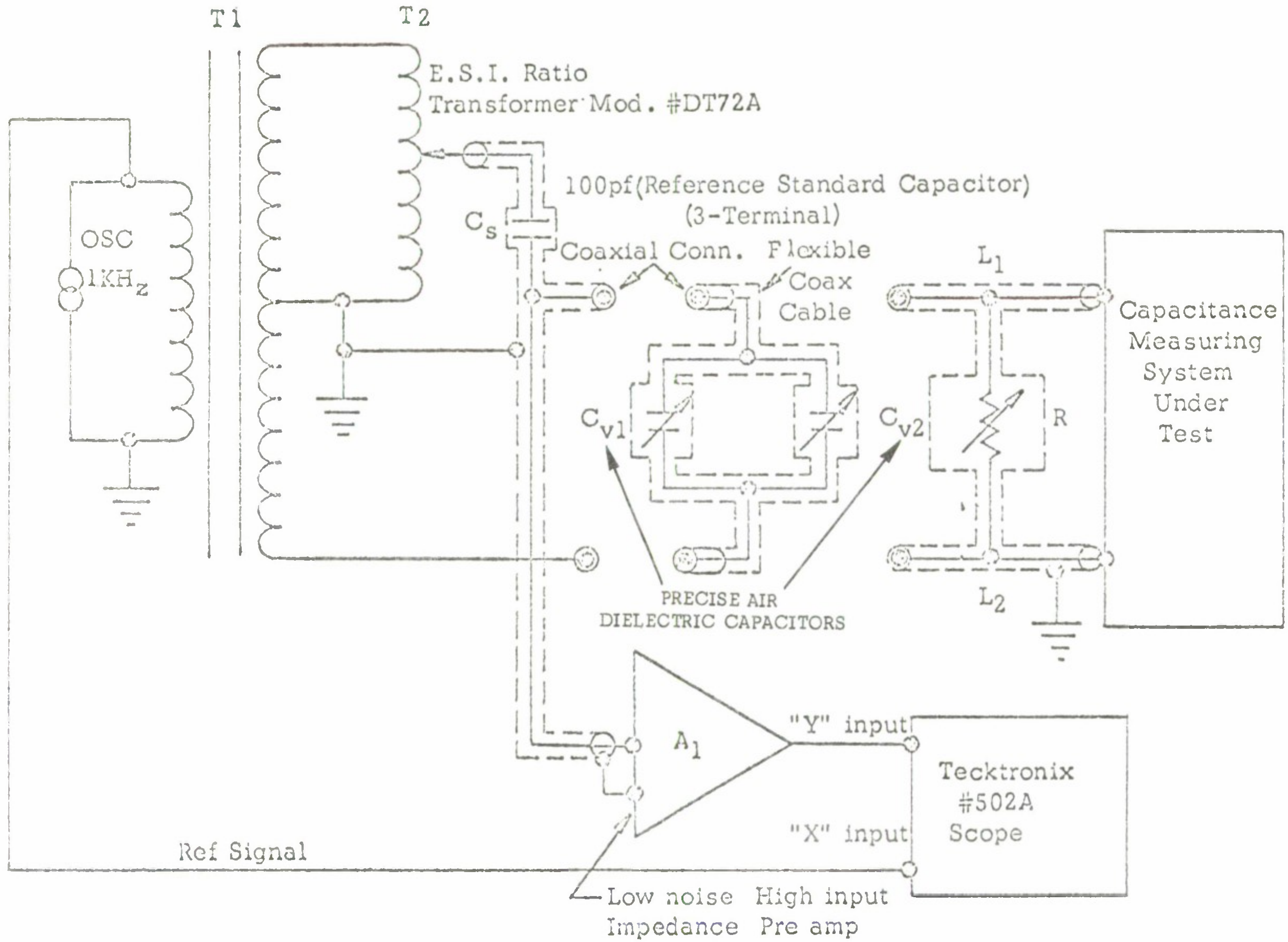


Figure 18 Test Circuit

Step 2: CV_1 and CV_2 were set exactly 5.000 pf and the voltmeter reading was noted.

Step 3: CV_2 was changed to 10, 15, 20, & 25 pf respectively, and the voltmeter reading at each point was noted. The voltmeter readings and the actual capacitance readings were compared by means of a least squares fit.

Test 69 - same as Test 68, except the frequency was changed from 1 kHz to 150 kHz.

Test 70 - Interference

Step 1: A 20 pf mica capacitor was connected to the second system.

Step 2: The frequency of the second system was set at 1 kHz.

Step 3: Test 1, Steps 1 through 4 were repeated on the first system.

Step 4: The second system was switched to each of the other 3 frequencies respectively and the voltmeter reading was noted in each case. Note: Since the cables connecting the remote units to the readout panel were carrying d. c. signals only and since the remote units were completely shielded, the only possibility for interaction was due to close proximity of the capacitors simulating the strain gages or the close proximity of the strain gages themselves in actual use. Consequently, this test was repeated using two 20 pf capacitances simulating the gage and noting how close these capacitors can be before signs of interaction occurred.

Tests 1 through 69 were repeated on Unit No. 2.

SECTION VII

TEST RESULTS

The test data is presented in the Appendix. The tests verified the various operational modes of the Automatic Capacitance Measurement System. A summary of the test results is presented herein.

1. Basic Accuracy and Linearity At 1 KHz.

Tests 1 through 21 of the test plan were intended to measure the basic accuracy and linearity at 1 KHz. The results of these tests are summarized in Table V. The accuracy is given as the deviation from the theoretical value in pf and as a percentage of the full scale output (30 pf). The linearity is given as the maximum deviation from the theoretical value both in pf and in a percentage of the span of the measurand. The span is 4 pf when the unit was operated in the differential mode and 25 pf when the unit was operated in the total capacitance mode.

TABLE V. ACCURACY AT 1 KHz (TOTAL CAPACITANCE MODE)

	Unit No. 1		Unit No. 2	
Accuracy @ 10 pf	+.10 pf	+.33%	+.13 pf	+.43%
Accuracy @ 20 pf	+.02 pf	+.06%	+.06 pf	+.20%
Accuracy @ 30 pf	+.03 pf	+.10%	-.03 pf	-.10%
Accuracy @ 30 pf w/loss resistor	-.51 pf	-1.70%	-.40 pf	-1.33%
LINEARITY AT 1 KHz (DIFFERENTIAL CAPACITANCE MODE)				
Linearity @ 10 ±2 pf	±.01 pf	±.25%	±.02 pf	±.50%
Linearity @ 20 ±2 pf	±.02 pf	±.50%	±.01 pf	±.25%
Linearity @ 30 ±2 pf	±.01 pf	±.25%	±.05 pf	±1.25%
Linearity @ 30 ±2 pf w/loss resistor	±.05 pf	±1.25%	±.09 pf	±1.75%
Linearity @ 20 ±12 pf (Total Mode)	±.05 pf	±.21%	±.11 pf	±.46%

2. Accuracy and Linearity vs Frequency

Table VI presents the accuracy and linearity of the capacitance system at 30 pf as the frequency is varied through its ranges of 1, 5, 30, and 150 KHz.

3. Resolution vs Frequency

Table VII presents the resolution of the system vs frequency. The capacitance was increased .005 pf and the system output monitored. The table lists the actual output change in both the TOTAL CAPACITANCE mode and the DIFFERENTIAL CAPACITANCE mode.

4. Temperature Effects

The units were subjected to ambient temperature variations from 10°C to 40°C and the output was monitored. The indicated output changed less than ±.03 pf, ±.1% over the temperature range.

TABLE VI. ACCURACY AND LINEARITY VS FREQUENCY

	FREQUENCY	UNIT NO. 1		UNIT NO. 2	
Accuracy	1 KHz	+.03pf	+.10%	-.03pf	-.10%
	5 KHz	+.08pf	+.27%	-.02pf	-.07%
	30 KHz	-.14pf	-.47%	-.18pf	-.60%
	150 KHz	-.08pf	-.27%	+.01pf	+.03%
Linearity	1 KHz	±.01pf	±.25%	±.05pf	±1.25%
	5 KHz	±.01pf	±.25%	±.02pf	±.50%
	30 KHz	±.02pf	±.50%	±.04pf	±1.00%
	150 KHz	±.03pf	±.75%	±.02pf	±.50%
Accuracy w/loss resistor	1 KHz	-.51pf	-1.70%	-.40pf	-1.33%
	5 KHz	+.11pf	+.37%	+.07pf	+.23%
	30 KHz	-.29pf	-.97%	-.40pf	-1.33%
	150 KHz	-1.09pf	-3.63%	-1.02pf	-3.40%
Linearity w/loss resistor	1 KHz	±.05pf	±1.25%	±.09pf	±1.75%
	5 KHz	±.02pf	±.50%	±.03pf	±.75%
	30 KHz	±.01pf	±.25%	±.03pf	±.75%
	150 KHz	±.02pf	±.50%	±.01pf	±.25%

TABLE VII. RESOLUTION VS FREQUENCY FOR .005pf CHANGE

	FREQUENCY	UNIT NO. 1	UNIT NO. 2
Total Cap Mode	1	.008pf	.005pf
	5	.009pf	.010pf
	30	.008pf	.011pf
	150	.007pf	.012pf
Diff. Cap Mode	1	.006pf	.005pf
	5	.005pf	.007pf
	30	.005pf	.007pf
	150	.005pf	.007pf

5. Response Time

The time for the system to respond to a step change in capacitance was monitored in tests 59, 60 and 61. In all cases the unit responded in less than 1 second to its final value for a 0.2 pf change.

6. Recorder Sensitivity

The recorder outputs were monitored in tests 62, 63, and 64 and the simulated sensor capacitance was changed 0.2pf. The recorder outputs should have changed 0.01 volts which they did exactly in all cases. This test was conducted at 1KHz with a simulated capacitance of 10pf and 30pf and at 150 KHz with a simulated capacitance of 10pf.

7. Recorder Drift

The recorder outputs were monitored for one hour at 1KHz at 10pf and 30pf and also at 150KHz at 10pf. At 1KHz and 10pf Unit No. 1 drifted +200μV and Unit No. 2 drifted +100μV; at 30pf Unit No. 1 drifted +200μV and Unit No. 2 drifted +300μV. With the frequency at 150KHz Unit No. 1 output drifted +200μV and Unit No. 2 output drifted -700μV.

8. Linearity

Capacitance readings were made at 10, 15, 20, 25 and 30 pf, at 1 and 150 KHz. The linearity of the output was measured at the recorder output. For Unit No. 1 the 1KHz linearity was ±0.91mV and at 150 KHz the linearity was ±2.60mV. For Unit No. 2 the 1KHz linearity was ±1.01mV and at 150KHz the linearity was ±0.81mV.

9. Interaction

With Unit No. 1 at 1KHz and Unit No. 2 at 150 KHz the two units were operated and the cables moved closer together and the output of each unit was monitored in turn. There was no indication of interaction up to the point the shields touched. When the two shields touched a 60 Hz signal was created in the ground loop which saturated the amplifier.

SECTION VIII

SUMMARY AND CONCLUSIONS

The performance of the automatic capacitance measuring system was not within the target specifications in all areas. The performance of the system was evaluated at what was considered the extremes of performance; evaluation was conducted at the maximum and minimum of the capacitance range where linearity and absolute accuracy suffer the greatest degradation. The areas giving rise to the inaccuracies are those which were initially outlined as potential problem areas. The problems in these areas are not insurmountable but become prohibitive in the complexity, and in the stability and reproduci-ability of the instrument.

The major problem area was in attempting to attain satisfactory operation at 1MHz. It was possible to obtain stability in one mode of operation at 1MHz at the expense of creating inaccuracies at other frequencies, and having an unstable system in other modes. It was concluded, after attempting many forms of phase compensation, that 1MHz operation was not feasible with 50 foot sensor leads. Since some modes were stable, however, it is implied that the possibility of success at 1MHz using 25 foot leads is considerably greater.

The automatic quadrature balance network using the photocell, light combination does reach a quadrature null as it should. The difficulty in this area is the photocell has inherent capacity which varies as a function of the impedance. This small, but variable, capacitance creates errors in the absolute and differential capacitance modes of operation as the loss angle of the gage changes. Even though the errors are quite small, another method of creating the quadrature signal would be advantageous.

It would appear that limiting the operation to a singular frequency would lessen the problem and make compensation for linearity and absolute accuracy very feasible and quite practical.

The technique of converting an AC power to DC output voltage in a self balancing bridge network performed admirably. The errors arising from this network did not fall into a recognizable pattern, being a random, yet stable, error. The subsequent gain and transferring the output into absolute capacitance, differential capacitance and strain outputs from one input gave no significant difficulty.

The capacitance used as a reference, which is a nominal 18.000 pf, and the sections which enable selections of 20.000pf and 22.000pf are convenient for measuring strain, setting the gage factor, and calibrating. They have proved to be frequency and time stable.

The ability to use a dual bridge transducer in the system with one bridge as the sensor for each of the remote units appears feasible with the major problem appearing as a ground loop problem. Any signal which appears on the high temperature coaxial lines as a result of an induced voltage will be amplified by the input of the balance amplifier. The system will cease to function if this signal becomes large enough to cause saturation. With a single bridge, it is possible to minimize this problem by keeping the coaxial cables together as a single cable which keeps the aperature of the "loop" to a minimum. However, if a dual bridge is used, then the grounding between the two remote units must be to the same point and the cable runs to the capacitance gage must be made as a cable composed of six high temperature coaxial cables, again to keep the aperature of the "loop" to a minimum.

The interaction between the two units without shields touching was not measureable during bench tests. When the shields were allowed to touch, the input amplifier was saturated with power line frequency induced signals. As is the case with most problems of this nature, the ability to operate in this mode will best be determined by tests in the actual installation.

Although the system appears to work the best at, and to be more manageable at, the lower frequencies it can be optimized at any one frequency. From the indicators in the test results it is felt that single frequency operation would be the biggest boon to achieving the desired accuracies.

It is also felt that under actual operating conditions, where the strain gages are nearer the center of the capacitance range, and the loss factors do not reach their extremes, that the system will perform much better than the test results indicate. Also under these conditions those parameters which are of repeated concern and those which only attain limited importance will emerge. From this data the system can then be optimized for frequency, range, linearity, and all parameters.

REFERENCES

1. Gillette and Vaughn, "Research and Development of a High Temperature Capacitance Strain Gage," Air Force Flight Dynamics Laboratory Technical Report, AFFDL-TR-68-27, February 1968, AD834962.

2. Valley and Wallman, Vacuum Tube Amplifier, McGraw Hill, 1948.

APPENDIX

TEST DATA

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 1 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
1	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	18pf STD	Sensitivity	-	+1.800	+1.799	-		
	3		-	-	CT	20pf		-	+2.000	+2.000	0	±3	
	4		-	-	CT	22pf		-	+2.200	+2.199	- 1	±3	
	5		-	-	ΔC	22pf	Dif. Adj.	-	0.000	0.000			
	6		-	-	ΔC	20pf		-	-0.200	-0.199	+ 1	±3	
2	1		5.000	5.000	CT	Operate		-	+1.000	+1.010	+10	±3	
	2		5.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	0	±3	
	3		5.000	4.500	CT	Operate		-	+0.950	+0.960	+10	±3	
	4		5.000	4.500	ΔC	Operate		-	-0.050	-0.050	0	±3	
3	1		5.000	5.500	CT	Operate		-	+1.050	+1.060	+10	±3	
	2		5.000	5.500	ΔC	Operate		-	+0.050	+0.050	0	±3	
4	1		5.000	4.000	CT	Operate		-	+0.900	+0.910	+10	±3	
	2		5.000	4.000	ΔC	Operate		-	-0.100	-0.100	0	±3	
5	1		5.000	6.000	CT	Operate		-	+1.100	+1.110	+10	±3	
	2		5.000	6.000	ΔC	Operate		-	+0.100	+0.100	0	±3	
6	1		5.000	3.500	CT	Operate		-	+0.850	+0.860	+10	±3	
	2		5.000	3.500	ΔC	Operate		-	-0.150	-0.150	0	±3	
7	1		5.000	6.500	CT	Operate		-	+1.150	+1.159	+ 9	±3	
	2		5.000	6.500	ΔC	Operate		-	+0.150	+0.149	- 1	±3	
8	1		5.000	3.000	CT	Operate		-	+0.800	+0.811	+11	±3	
	2		5.000	3.000	ΔC	Operate		-	-0.200	-0.199	+ 1	±3	
9	1		5.000	7.000	CT	Operate		-	+1.200	+1.209	+ 9	±3	
	2		5.000	7.000	ΔC	Operate		-	+0.200	+0.199	+ 1	±3	
10	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
11	1		15.000	5.000	CT	Operate		-	+2.000	+2.002	+ 2	±3	
	2		15.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		15.000	4.500	CT	Operate		-	+1.950	+1.955	+ 5	±3	
	4		15.000	4.500	ΔC	Operate		-	-0.050	-0.049	+ 1	±3	

a) Refer to test plan for description of test.
b) CT represents "Total Capacitance;" ΔC represents "Differential Capacitance."

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 2 OF 7)

(a) Test No.	(a) Step No.	Freq (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
12	1	1	15.000	3.000	CT	Operate		-	+1.800	+1.806	+ 6	±3	
	2		15.000	3.000	ΔC	Operate		-	-0.200	-0.199	+ 1	±3	
13	1		15.000	7.000	CT	Operate		-	+2.200	+2.205	+ 5	±3	
	2		15.000	7.000	ΔC	Operate		-	+0.200	+0.201	+ 1	±3	
14	1		-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
15	1		25.000	5.000	CT	Operate		-	+3.000	+3.003	+ 3	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.953	+ 3	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.050	0	±3	
16	1		25.000	3.000	CT	Operate		-	+2.800	+2.804	+ 4	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.200	0		
17	1		25.000	7.000	CT	Operate		-	+3.200	+3.203	+ 3	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.201	+ 1	±3	
18	1		-	-	CT	Zero	Zero	5mΩ	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	5mΩ	+2.000	+2.000	-		
19	1		25.000	5.000	CT	Operate		5mΩ	+3.000	+2.949	-51	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	5mΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		5mΩ	+2.950	+2.902	-48	±3	
	4		25.000	4.500	ΔC	Operate		5mΩ	-0.050	-0.049	+ 1	±3	
20	1		25.000	3.000	CT	Operate		5mΩ	+2.800	_2.757	-43	±3	
	2		25.000	3.000	ΔC	Operate		5mΩ	-0.200	-0.194	+ 6	±3	
21	1		25.000	7.000	CT	Operate		5mΩ	+3.200	+3.147	-53	±3	
	2		25.000	7.000	ΔC	Operate		5mΩ	+0.200	+0.198	- 2	±3	
22	1	5	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 3 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Error Spec	Remarks
23	1	5	25.000	5.000	CT	Operate		-	+3.000	+3.008	+ 8	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.958	+ 8	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.050	0	±3	
24	1		25.000	3.000	CT	Operate		-	+2.800	+2.808	+ 8	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.201	- 1	±3	
25	1		25.000	7.000	CT	Operate		-	+3.200	+3.210	+10	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.203	+ 3	±3	
26	1		-	-	CT	Zero	Zero	1mΩ	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	1mΩ	+2.000	+2.000	-		
27	1		25.000	5.000	CT	Operate		1mΩ	+3.000	+3.011	+11	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	1mΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		1mΩ	+2.950	+2.962	+12	±3	
	4		25.000	4.500	ΔC	Operate		1mΩ	-0.050	-0.049	+ 1	±3	
28	1		25.000	3.000	CT	Operate		1mΩ	+2.800	+2.814	+14	±3	
	2		25.000	3.000	ΔC	Operate		1mΩ	-0.200	-0.198	+ 2	±3	
29	1		25.000	7.000	CT	Operate		1mΩ	+3.200	+3.212	+12	±3	
	2		25.000	7.000	ΔC	Operate		1mΩ	+0.200	+0.203	+ 3	±3	
30	1	30	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
31	1		25.000	5.000	CT	Operate		-	+3.000	+2.986	-14	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.938	-12	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.049	+ 1	±3	
32	1		25.000	3.000	CT	Operate		-	+2.800	+2.789	-11	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.199	+ 1	±3	
33	1		25.000	7.000	CT	Operate		-	+3.200	+3.189	-11	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.203	+ 3	±3	
34	1		-	-	CT	Zero	Zero	150KΩ	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	150KΩ	+2.000	+2.000	-		

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 4 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
35	1		25.000	5.000	CT	Operate		150KΩ	+3.000	+2.971	-29	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	150KΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		150KΩ	+2.950	+2.922	-28	±3	
	4		25.000	4.500	ΔC	Operate		150KΩ	-0.050	-0.049	+ 1	±3	
36	1		25.000	3.000	CT	Operate		150KΩ	+2.800	+2.772	-28	±3	
	2		25.000	3.000	ΔC	Operate		150KΩ	-0.200	-0.201	- 1	±3	
37	1		25.000	7.000	CT	Operate		150KΩ	+3.200	+3.173	-27	±3	
	2		25.000	7.000	ΔC	Operate		150KΩ	+0.200	+0.202	+ 2	±3	
38	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
39	1		25.000	5.000	CT	Operate		-	+3.000	+2.992	- 8	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.943	- 7	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.050	0	±3	
40	1		25.000	3.000	CT	Operate		-	+2.800	+2.793	- 7	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.201	- 1	±3	
41	1		25.000	7.000	CT	Operate		-	+3.200	+3.198	- 2	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.203	+ 3	±3	
42	1		-	-	CT	Zero	Zero	33KΩ	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	33KΩ	+2.000	+2.000	-		
43	1		25.000	5.000	CT	Operate		33KΩ	+3.000	+2.891	-109	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	33KΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		33KΩ	+2.950	+2.843	-107	±3	
	4		25.000	4.500	ΔC	Operate		33KΩ	-0.050	-0.050	0	±3	
44	1		25.000	3.000	CT	Operate		33KΩ	+2.800	+2.693	-107	±3	
	2		25.000	3.000	ΔT	Operate		33KΩ	-0.200	-0.200	0	±3	
45	1		25.000	7.000	CT	Operate		33KΩ	+3.200	+3.095	-105	±3	
	2		25.000	7.000	ΔC	Operate		33KΩ	+0.200	+0.202	+ 2	±3	

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 5 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	Sensor Simulate (pf) CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Error ($V \times 10^{-3}$) Spec	Remarks
53	1	1	25.000	5.000	CT	Operate		-	+3.0000	+3.0054	+ 5.4		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-	(c)	
	3		25.000	5.005	CT	Operate		-	+3.0005	+3.0062	+ 5.7		
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0006	+ .1		
54	1	5	25.000	5.000	CT	Operate		-	+3.0000	+3.102	+10.2		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-	(c)	
	3		25.000	5.005	CT	Operate		-	+3.0005	+3.0111	+10.6		
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0005	0		
55	1	30	25.000	5.000	CT	Operate		-	+3.0000	+2.9952	- 4.8		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-	(c)	
	3		25.000	5.005	CT	Operate		-	+3.0005	+2.9960	- 4.0		
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0005	0		
56	1	150	25.000	5.000	CT	Operate		-	+3.0000	+2.9990	- 1.0		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-	(c)	
	3		25.000	5.005	CT	Operate		-	+3.0005	+2.9997	- .8		
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0005	0		
58	2	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
			-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		23°C
			-	-	CT	18pf		-	+1.800	+1.800	-		
			-	-	CT	22pf		-	+2.200	+2.200	-		
	3		-	-	CT	Zero		-	0.000	+0.002	+ 2	±3	
			-	-	CT	20pf		-	+2.000	+2.003	+ 3	±3	40°C
			-	-	CT	18pf		-	+1.800	+1.802	+ 2	±3	
			-	-	CT	22pf		-	+2.200	+2.203	+ 3	±3	
	4		-	-	CT	Zero		-	0.000	+0.002	+ 2	±3	
			-	-	CT	20pf		-	+2.000	+1.998	- 2	±3	10°C
			-	-	CT	18pf		-	+1.800	+1.797	- 3	±3	
			-	-	CT	22pf		-	+2.200	+2.198	- 2	±3	

c) Difference Step 1 to 3 and Step 2 to 4 is .5 ± .2

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 6 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	Sensor Simulate (pf) CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Error ($V \times 10^{-3}$) Spec	Remarks
59	1	1	-	-	CT	Zero	Zero	-	0.000	0.000			
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000			(d)
	3		5.000	5.000	CT	Operate		-	+1.000	+1.009			
	4		5.000	5.000	CT	Operate		-	+1.020	+1.028			
	5		5.000	5.000	CT	Operate		-	+1.000	+1.009			
	6		5.000	5.000	CT	Operate		-	+1.020	+1.028			
60	1		-	-	CT	Zero	Zero	-	0.000	0.000			
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000			
	3		25.000	5.000	CT	Operate		-	+3.000	+3.001			(d)
	4		25.000	5.000	CT	Operate		-	+3.020	+3.021			
	5		25.000	5.000	CT	Operate		-	+3.000	+3.002			
	6		25.000	5.000	CT	Operate		-	+3.020	+3.022			
61	1	150	-	-	CT	Zero	Zero	-	0.000	0.000			
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000			
	3		5.000	5.000	CT	Operate		-	+1.000	+0.998			(d)
	4		5.000	5.000	CT	Operate		-	+1.020	+1.016			
	5		5.000	5.000	CT	Operate		-	+1.000	+0.998			
	6		5.000	5.000	CT	Operate		-	+1.020	+1.016			
62	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.500	+0.500	0	±1.5	
	3		5.000	5.200	CT	Operate		-	+0.510	+0.510	0	±1.5	
63	1		25.000	5.000	CT	Operate		-	+1.500	+1.500	0	±1.5	
			25.000	5.200	CT	Operate		-	+1.510	+1.510	0	±1.5	
64	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.500	+0.500	0	±1.5	
	3		5.000	5.200	CT	Operate		-	+0.510	+0.510	0	±1.5	
65	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.5045	+ 4.5		
	3		5.000	5.200	CT	Operate		-	+0.5100	+0.5146	+ 4.6	(e)	
	4		5.000	5.200	CT	Operate		-	+0.5100	+0.5148	+ 4.8	± .25	

d) Response time was verified less than 1 second for step change of .2 pF in addition to values of CV_1 and CV_2.

e) Difference Step 3 to 4 should be less than 250μV, i.e. $.25 \times 10^{-3}$V.

TABLE VIII. REMOTE UNIT NO. 1 TEST DATA (SHEET 7 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	Sensor Simulate (pf) CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Error ($V \times 10^{-3}$) Spec	Remarks
66	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		25.000	5.000	CT	Operate		-	+1.5000	+1.5026	+ 2.6	(e)	
	3		25.000	5.200	CT	Operate		-	+1.5100	+1.5127	+ 2.7		
	4		25.000	5.200	CT	Operate		-	+1.5100	+1.5129	+ 2.9	±.25	
67	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.4988	- 1.2		
	3		5.000	5.200	CT	Operate		-	+0.5100	+0.5086	- 1.4	(e)	
	4		5.000	5.200	CT	Operate		-	+0.5100	+0.5088	- 1.2	±.25	
68	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.5047	+ 4.7	(f)	
	3		10.000	5.000	CT	Operate		-	+0.7500	+0.7536	+ 3.6		
			15.000	5.000	CT	Operate		-	+1.0000	+1.0041	+ 4.1	±1.5	
			20.000	5.000	CT	Operate		-	+1.2500	+1.2543	+ 4.3		
			25.000	5.000	CT	Operate		-	+1.5000	+1.5027	+ 2.7		
69	1	150	-	-	CT	Zero	Zero	-	0.000	0.000			
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000			
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.4995	- .5		
	3		10.000	5.000	CT	Operate		-	+0.7500	+0.7454	- 4.5	(f)	
			15.000	5.000	CT	Operate		-	+1.0000	+0.9966	- 3.4		
			20.000	5.000	CT	Operate		-	+1.2500	+1.2483	- 1.7	±1.5	
			25.000	5.000	CT	Operate		-	+1.5000	+1.5007	- 0.7		
70	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	3		-	-	CT	18pf		-	+1.800	+1.799	- 1		(g)
	4		-	-	CT	22pf		-	+2.200	+2.200	0		
	5		-	-	CT	22pf		-	+2.200	+2.200	0		

f) Deviation from linear response, best straight line.
g) No interaction noted unless shields touched.

TABLE IX. REMOTE UNIT NO. 2 TEST DATA (SHEET 1 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error($V \times 10^{-3}$) Actual	Spec	Remarks
1	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	18pf	Sensitivity	-	+1.800	+1.800	-		
	3		-	-	CT	20pf		-	+2.000	+2.000	0	±3	
	4		-	-	CT	22pf		-	+2.200	+2.199	-1	±3	
	5		-	-	ΔC	22pf	Dif. Adj.	-	0.000	0.000	-		
	6		-	-	ΔC	20pf		-	-0.200	-0.199	+1	±3	
2	1		5.000	5.000	CT	Operate		-	+1.000	+1.013	+13	±3	
	2		5.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		5.000	4.500	CT	Operate		-	+0.950	+0.963	+13	±3	
	4		5.000	4.500	ΔC	Operate		-	-0.050	-0.050	0	±3	
3	1		5.000	5.500	CT	Operate		-	+1.050	+1.063	+13	±3	
	2		5.000	5.500	ΔC	Operate		-	+0.050	+0.049	-1	±3	
4	1		5.000	4.000	CT	Operate		-	+0.900	+0.914	+14	±3	
	2		5.000	4.000	ΔC	Operate		-	-0.100	-0.100	0	±3	
5	1		5.000	6.000	CT	Operate		-	+1.100	+1.113	+13	±3	
	2		5.000	6.000	ΔC	Operate		-	+0.100	+0.099	-1	±3	
6	1		5.000	3.500	CT	Operate		-	+0.850	+0.864	+14	±3	
	2		5.000	3.500	ΔC	Operate		-	-0.150	-0.150	0	±3	
7	1		5.000	6.500	CT	Operate		-	+1.150	+1.162	+12	±3	
	2		5.000	6.500	ΔC	Operate		-	+0.150	+0.149	-1	±3	
8	1		5.000	3.000	CT	Operate		-	+0.800	+0.815	+15	±3	
	2		5.000	3.000	ΔC	Operate		-	-0.200	-0.199	+1	±3	
9	1		5.000	7.000	CT	Operate		-	+1.200	+1.212	+12	±3	
	2		5.000	7.000	ΔC	Operate		-	+0.200	+0.198	-2	±3	
10	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
11	1		15.000	5.000	CT	Operate		-	+2.000	+2.006	+6	±3	
	2		15.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		15.000	4.500	CT	Operate		-	+1.950	+1.957	+7	±3	
	4		15.000	4.500	ΔC	Operate		-	-0.050	-0.051	-1	±3	

a) Refer to test plan for description of test.
b) CT represents "Total Capacitance;" ΔC represents "Differential Capacitance."

TABLE IX. REMOTE UNIT NO. 2 TEST DATA (SHEET 2 OF 7)

(a) Test No.	(a) Step No.	Freq.	Sensor Simulate (pf) CV_1	Sensor Simulate (pf) CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error ($V \times 10^{-3}$) Actual	Error ($V \times 10^{-3}$) Spec	Remarks
12	1	1	15.000	3.000	CT	Operate		-	+1.800	+1.807	+7	±3	
	2		15.000	3.000	ΔC	Operate		-	-0.200	-0.202	-2	±3	
13	1		15.000	7.000	CT	Operate		-	+2.200	+2.205	+5	±3	
	2		1 .000	7.000	ΔC	Operate		-	+0.200	+0.197	-3	±3	
14	1		-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
15	1		25.000	5.000	CT	Operate		-	+3.000	+2.997	-3	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.949	-1	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.051	-1	±3	
16	1		25.000	3.000	CT	Operate		-	+2.800	+2.802	+2	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.198	±2	±3	
17	1		25.000	7.000	CT	Operate		-	+3.200	+3.193	-7	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.194	-6	±3	
18	1		-	-	CT	Zero	Zero	5mΩ	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	5mΩ	+2.000	+2.000	-		
19	1		25.000	5.000	CT	Operate		5mΩ	+3.000	+2.960	-40	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	5mΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		5mΩ	+2.950	+2.910	-40	±3	
	4		25.000	4.500	ΔC	Operate		5mΩ	-0.050	-0.050	0	±3	
20	1		25.000	3.000	CT	Operate		5mΩ	+2.800	+2.766	-34	±3	
	2		25.000	3.000	ΔC	Operate		5mΩ	-0.200	-0.195	+5	±3	
21	1		25.000	7.000	CT	Operate		5mΩ	+3.200	+3.149	-51	±3	
	2		25.000	7.000	ΔC	Operate		5mΩ	+0.200	+0.190	-10	±3	
22	1	5	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		

TABLE IX. REMOTE UNIT NO. 2 TEST DATA (SHEET 3 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
23	1	5	25.000	5.000	CT	Operate		-	+3.000	+2.998	-2	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.948	-2	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.051	-1	±3	
24	1		25.000	3.000	CT	Operate		-	+2.800	+2.799	-1	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.200	0	±3	
25	1		25.000	7.000	CT	Operate		-	+3.200	+3.196	-4	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.198	-2	±3	
26	1		-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
27	1		25.000	5.000	CT	Operate		1mΩ	+3.000	+3.007	+7	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	1mΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		1mΩ	+2.950	+2.958	+8	±3	
	4		25.000	4.500	ΔC	Operate		1mΩ	-0.050	-0.050	0	±3	
28	1		25.000	3.000	CT	Operate		1mΩ	+2.800	+2.809	+9	±3	
	2		25.000	3.000	ΔC	Operate		1mΩ	-0.200	-0.199	+1	±3	
29	1		25.000	7.000	CT	Operate		1mΩ	+3.200	+3.204	+4	±3	
	2		25.000	7.000	ΔC	Operate		1mΩ	+0.200	+0.197	-3	±3	
30	1	30	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
31	1		25.000	5.000	CT	Operate		-	+3.000	+2.982	-18	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.933	-17	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.050	0	±3	
32	1		25.000	3.000	CT	Operate		-	+2.800	+2.783	-17	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.200	0	±3	
33	1		25.000	7.000	CT	Operate		-	+3.200	+3.175	-25	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.193	-7	±3	

TABLE IX. REMOTE UNIT NO 2 TEST DATA (SHEET 4 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
34	1	30	-	-	CT	Zero	Zero	150KΩ	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	150KΩ	+2.000	+2.000	-		
35	1		25.000	5.000	CT	Operate		150KΩ	+3.000	+2.960	-40	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	150KΩ	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		150KΩ	+2.950	+2.911	-39	±3	
	4		25.000	4.500	ΔC	Operate		150KΩ	-0.050	-0.050	0	±3	
36	1		25.000	3.000	CT	Operate		150KΩ	+2.800	+2.762	-38	±3	
	2		25.000	3.000	ΔC	Operate		150KΩ	-0.200	-0.199	+1	±3	
37	1		25.000	7.000	CT	Operate		150KΩ	+3.200	+3.156	-44	±3	
	2		25.000	7.000	ΔC	Operate		150KΩ	+0.200	+0.195	-5	±3	
38	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
39	1		25.000	5.000	CT	Operate		-	+3.000	+3.001	+1	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		-	+2.950	+2.949	-1	±3	
	4		25.000	4.500	ΔC	Operate		-	-0.050	-0.051	-1	±3	
40	1		25.000	3.000	CT	Operate		-	+2.800	+2.798	-2	±3	
	2		25.000	3.000	ΔC	Operate		-	-0.200	-0.202	-2	±3	
41	1		25.000	7.000	CT	Operate		-	+3.200	+3.199	-1	±3	
	2		25.000	7.000	ΔC	Operate		-	+0.200	+0.199	-1	±3	
42	1		-	-	CT	Zero	Zero	33.000Ω	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	33.000Ω	+2.000	+2.000	-		
43	1		25.000	5.000	CT	Operate		33.000Ω	+3.000	+2.898	-102	±3	
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	33.000Ω	0.000	0.000	-		
	3		25.000	4.500	CT	Operate		33.000Ω	+2.950	+2.847	-103	±3	
	4		25.000	4.500	ΔC	Operate		33.000Ω	-0.050	-0.051	-1	±3	
44	1		25.000	3.000	CT	Operate		33.000Ω	+2.800	+2.697	-103	±3	
	2		25.000	3.000	ΔC	Operate		33.000Ω	-0.200	-0.202	-2	±3	

TABLE IX. REMOTE UNIT NO. 2 TEST DATA (SHEET 5 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustments	Loss Resistor	DVM Reading Ideal	DVM Reading Actual	Error (V x 10^{-3}) Actual	Spec	Remarks
45	1	150	25.000	7.000	CT	Operate		33.000Ω	+3.200	+3.097	-103	±3	
	2		25.000	7.000	ΔC	Operate		33.000Ω	+0.200	+0.200	0	±3	
53	1	1	25.000	5.000	CT	Operate		-	+3.000	+2.9985	-1.5		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.000	0.000	-		
	3		25.000	5.005	CT	Operate		-	+3.0005	+2.9990	-1.5	(c)	
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0005	0		
54	1	5	25.000	5.000	CT	Operate		-	+3.0000	+2.9972	-2.8		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-	(c)	
	3		25.000	5.005	CT	Operate		-	+3.0005	+2.9982	-2.3		
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0007	+ .2		
55	1	30	25.000	5.000	CT	Operate		-	+3.0000	+2.9817	-18.3		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-	(c)	
	3		25.000	5.005	CT	Operate		-	+3.0005	+2.9828	17.7		
	4		25.000	5.005	ΔC	Operate		-	+0.0005	0.0007	+ .2		
56	1	150	25.000	5.000	CT	Operate		-	+3.0000	+2.9993	- .7		
	2		25.000	5.000	ΔC	Operate	Dif. Adj.	-	0.0000	0.0000	-		
	3		25.000	5.005	CT	Operate		-	+3.0005	+3.0005	0	(c)	
	4		25.000	5.005	ΔC	Operate		-	+0.0005	+0.0007	+ .2		
58	2	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
			-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
			-	-	CT	18pf		-	+1.800	+1.801	-		23°C
			-	-	CT	22pf		-	+2.200	+2.199	-		
	3		-	-	CT	Zero		-	0.000	+0.001	+1	±3	
			-	-	CT	20pf		-	+2.000	+2.001	+1	±3	40°C
			-	-	CT	18pf		-	+1.800	+1.803	+3	±3	
			-	-	CT	22pf		-	+2.200	+2.200	0	±3	
	4		-	-	CT	Zero		-	0.000		+1	±3	
			-	-	CT	20pf		-	+2.000 µ	+1.998	-2	±3	10°C
			-	-	CT	18pf		-	+1.800	+1.799	-1	±3	
			-	-	CT	22pf		-	+2.200	+2.197	-3	±3	
59	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	3		5.000	5.000	CT	Operate		-	+1.000	+1.011	+11		

c) Difference Step 1 to 3 and Step 2 to 4 is .5 ± .2.

TABLE IX. REMOTE UNIT NO. 2 TEST DATA (SHEET 6 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
59	4	1	5.000	5.000	CT	Operate		-	+1.020	+1.030	+10		
	5		5.000	5.000	CT	Operate		-	+1.000	+1.011	+11		(d)
	6		5.000	5.000	CT	Operate		-	+1.020	+1.030	+10		
60	1		-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	3		25.000	5.000	CT	Operate		-	+3.000	+2.999	-1		(d)
	4		25.000	5.000	CT	Operate		-	+3.020	+3.018	-2		
	5		25.000	5.000	CT	Operate		-	+3.000	+2.999	-1		
	6		25.000	5.000	CT	Operate		-	+3.020	+3.018	-2		
61	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	2		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	3		5.000	5.000	CT	Operate		-	+1.000	+0.996	-4		(d)
	4		5.000	5.000	CT	Operate		-	+1.020	+1.015	-5		
	5		5.000	5.000	CT	Operate		-	+1.000	+0.996	-4		
	6		5.000	5.000	CT	Operate		-	+1.020	+1.014	-6		
62	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.500	+0.507	+7	±1.5	
	3		5.000	5.200	CT	Operate		-	+0.510	+0.517	+7	±1.5	
63	1		25.000	5.000	CT	Operate		-	+1.500	+1.499	-1	±1.5	
			25.000	5.200	CT	Operate		-	+1.510	+1.509	-1	±1.5	
64	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.500	+0.498	-2	±1.5	
	3		5.000	5.200	CT	Operate		-	+0.510	+0.508	-2	±1.5	
65	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.5007	+ .7	(e)	
	3		5.000	5.200	CT	Operate		-	+0.5100	+0.5108	+ .8	±.25	
	4		5.000	5.200	CT	Operate		-	+0.5100	+0.5109	+ .9		

d) Response time was verified less than 1 second for step change of .2 pF in addition to values of CV_1 and CV_2.

e) Difference Step 3 to 4 should be less than 250µV, i.e. 25×10^{-3}V.

TABLE IX. REMOTE UNIT NO. 2 TEST DATA (SHEET 7 OF 7)

(a) Test No.	(a) Step No.	Freq. (KHz)	Sensor Simulate (pf) CV_1	CV_2	(b) Mode Switch	Function Switch	Adjustment	Loss Resistor	DVM Reading Ideal	Actual	Error ($V \times 10^{-3}$) Actual	Spec	Remarks
66	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		25.000	5.000	CT	Operate		-	+1.5000	+1.4980	-2.0	(e)	
	3		25.000	5.200	CT	Operate		-	+1.5100	+1.5080	-2.0		
	4		25.000	5.200	CT	Operate		-	+1.5100	+1.5083	-1.7	±.25	
67	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.4983	-1.7	(e)	
	3		5.000	5.200	CT	Operate		-	+0.5100	+0.5082	-1.8		
	4		5.000	5.200	CT	Operate		-	+0.5100	+0.5075	-2.5	±.25	
68	1	1	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-		
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.5062	+6.2	(f)	
	3		10.000	5.000	CT	Operate		-	+0.7500	+0.7540	+4.0	±1.5	
			15.000	5.000	CT	Operate		-	+1.0000	+1.0033	+3.3		
			20.000	5.000	CT	Operate		-	+1.2500	+1.2523	+2.3		
			25.000	5.000	CT	Operate		-	+1.5000	+1.4986	-1.4		
69	1	150	-	-	CT	Zero	Zero	-	0.000	0.000	-		
	1		-	-	CT	20pf	Sensitivity	-	+2.000	+2.000	-	(f)	
	2		5.000	5.000	CT	Operate		-	+0.5000	+0.4983	-1.7	±1.5	
	3		10.000	5.000	CT	Operate		-	+0.7500	+0.7474	-2.6		
			15.000	5.000	CT	Operate		-	+1.0000	+0.9986	-1.4		
			20.000	5.000	CT	Operate		-	+1.2500	+1.2500	0		
			25.000	5 000	CT	Operate		-	+1.5000	+1.5011	+1.1		
70		1/150	20.000	Simulated Sensor	CT	Operate							(g)

f) Deviation from linear response, best straight line.
g) No indication noted unless shields touched.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* The Bissett-Berman Corporation 3939 Ruffin Road, San Diego, Ca. 92123	2a. REPORT SECURITY CLASSIFICATION None 2b. GROUP

3. REPORT TITLE

Automatic Capacitance Measuring System

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final

5. AUTHOR(S) *(First name, middle initial, last name)*

Roger A. Hala

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1971	55	1

8a. CONTRACT OR GRANT NO. F33615-69-C-1298 b. PROJECT NO. 1347 c. Task 134702 d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFFDL-TR-71-101 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Flight Dynamics Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

This report describes the development of an automatic capacitance measurement system. The system was specifically designed to be compatible with a capacitive strain gage working in ambient temperatures up to 1500°F. The progression of the development yielded a system capable of measuring three terminal capacitors at a distance of up to 150 feet. Two systems were constructed and delivered to the Air Force Flight Dynamics Laboratory. The system measures capacitances from 10 to 30 pf and automatically balances the loss component. Four frequencies of operation are selectable for system operation. The outputs of the system are a D.C. voltage of 50 mv/pf and a digital indication of capacitance. The results of tests indicated the automatic measurement of remote capacitance to a high degree of accuracy is, in every respect, technically practical. All of the target specifications were not met; however, the performance anomalies occurred at the extremes of measurement.

DD FORM 1 NOV 65 1473

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Strain gage						
Capacitance						
Remote capacitance measurement						
Loss component compensation						
Multifrequency capacitance measurement						
High temperature capacitance measurement						
Automatic capacitance measurement						
Remote capacitance measurement data						

☆U.S.Government Printing Office: 1972 — 759-081/307

Unclassified
Security Classification