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THE CONSTANT CURRENT LOOP: A NEW PARADIGM FOR RESISTANCE SIGNAL CONDITINING

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ABSTRACT

A practical single constant current loop circuit for the signal conditioning of variable-resistance transducers has been synthesized, analyzed, and demonstrated. The strain gage and the resistance temperature device are examples of variable-resistance sensors. Lead wires connect variable-resistance sensors to remotely located signal-conditioning hardware. The presence of lead wires in the conventional Wheatstone bridge signal-conditioning circuit introduces undesired effects that reduce the quality of the data from the remote sensors. A practical approach is presented for suppressing essentially all lead wire resistance effects while indicating only the change in resistance value. Theoretical predictions supported by laboratory testing confirm the following features of the approach: (1) the dc response; (2) the electrical output is unaffected by extremely large variations in the resistance of any or all lead wires; (3) the electrical output remains zero for no change in gage resistance; (4) the electrical output is inherently linear with respect to gage resistance change; (5) the sensitivity is double that of a Wheatstone bridge circuit; and (6) the same excitation and sense wires can serve multiple independent gages. An adaptation of the current loop circuit is presented that simultaneously provides an output signal voltage directly proportional to transducer resistance change and provides temperature information that is unaffected by transducer and lead wire resistance variations. These innovations are the subject of NASA patent applications.

INTRODUCTION

Variable-resistance devices are convenient to use as transducers. Two common examples are the variable-resistance strain gage and the resistance temperature device (RTD). All variable-resistance transducers change resistance in response to a change in the sensitive parameter. When the change in resistance is a small percentage of the total transducer resistance, the signal-conditioning task becomes more of a challenge. A strain gage is an example of a transducer that exhibits these characteristics. The

significant output of a strain gage is the small resistance change, ΔR, that occurs in an initial resistance, R, as mechanical strain changes the dimensions of the gage. This small ΔR is typically no greater than 0.1 to 0.5 percent of R, which ranges typically from 120 to 1000 Ω.

The small magnitude of ΔR causes two general problems: the basic need to detect the small ΔR in the presence of the much larger initial gage resistance and the need to detect the desired ΔR in the presence of other parasitic resistance changes. Lead wire resistance changes, for example, can easily be larger than ΔR, especially where extreme temperature variations exist during a test. Serious errors due to lead wire resistance effects are common in the data from high-temperature strain measurements. High-temperature tests, such as those involving reentry simulations or operating turbine engines, often involve temperatures in excess of 1000 °F. References 1 and 2 point out the continuing need to deal with lead wire resistance effects, especially where testing involves extreme temperature changes.

The Wheatstone bridge, in various circuit forms, is the traditional circuit used to signal condition variable-resistance transducers such as strain gages and RTD's. Although the Wheatstone bridge has been used effectively for many years in the signal-conditioning role, it has some disadvantages in many situations that can be overcome by a constant current loop approach. The constant current loop approach presented here is insensitive to any lead wire resistance changes, the basic cause of problems when the Wheatstone bridge is used as a resistance signal-conditioning circuit for single remote resistances. Diagrams and equations, along with test data from a practical circuit, are presented to illustrate the principle of operation. An approach for including several transducers (such as a strain-gage rosette) in the same constant current loop is presented. Each transducer in the loop has an independent output for indication and recording. Finally, an adaptation of this circuit is presented that simultaneously delivers both transducer resistance change and transducer temperature when thermocouple wire is used with a single-gage resistance in a four-wire circuit.

The key contributions of Allen R. Parker, Jr., who implemented the equations of the constant current loop signal-conditioning concept with practical circuitry and software, are gratefully acknowledged.

WHEATSTONE BRIDGE

A basic function of the Wheatstone bridge as a signal conditioner is to transform the small resistance change of the variable-resistance transducer into a proportional voltage signal. The Wheatstone bridge was originally presented in reference 3.

Background

The Wheatstone bridge does an excellent job of subtracting two large voltages to yield an output voltage due to ΔR, the change in resistance. The Wheatstone bridge output, however, is inherently nonlinear for resistance changes in a single arm, and current-carrying lead wire resistances necessarily appear in the loop of the bridge circuit where they always reduce sensitivity and can cause zero shifts. Sir Charles Wheatstone states in reference 3, "Slight differences in the lengths and even in the tensions of the wires are sufficient to disturb the equilibrium [of my circuit]." Lead wire resistance effects are usually manageable for tests that involve moderate changes in lead wire and connector resistances. Wheatstone

bridge embodiments exist that reduce lead wire effects at the expense of added complexity in the signal-conditioning circuitry, additional lead wires, or both. Reference 4 discusses using a Wheatstone bridge with three lead wires connecting to a remote strain-gage resistance in a way that minimizes the effects of lead wire resistance variations.

A variation of the Wheatstone bridge described in reference 5 deals with lead wire resistance problems by replacing two resistance arms in the bridge with constant current sources. A fourth lead wire is used, and a third constant current source is employed to force the current to be zero in what would otherwise be a current-carrying lead wire. This tri-current method effectively tolerates lead wire resistance changes, delivers a linear output, and doubles sensitivity. Four lead wires, however, rather than three per measurement channel and three separate constant current sources that deliver very closely matched currents are required to obtain acceptable stability for strain measurements. The wiring, stability, and tracking requirements result in costs that have limited the application of the tri-current signal-conditioning technique.

Theory of Operation

The classic Wheatstone bridge circuit in figure 1 performs a precise analog subtraction of voltage drops across the various resistances in the loop of the bridge. This is done in a way that reliably isolates extremely small differences in large voltage drops. Commonly, microvolt (μV) level outputs are obtained from individual voltage drops of several volts. An ideal circuit is achieved for observing small variations in large resistances, especially when a minimum of parasitic lead wire resistance within the loop of the bridge is present.

The Wheatstone bridge circuit acts as an analog computation circuit. The excitation level serves as a multiplier to the circuit output, and variations in the four individual arms add to and subtract from the output according to their location in the circuit.
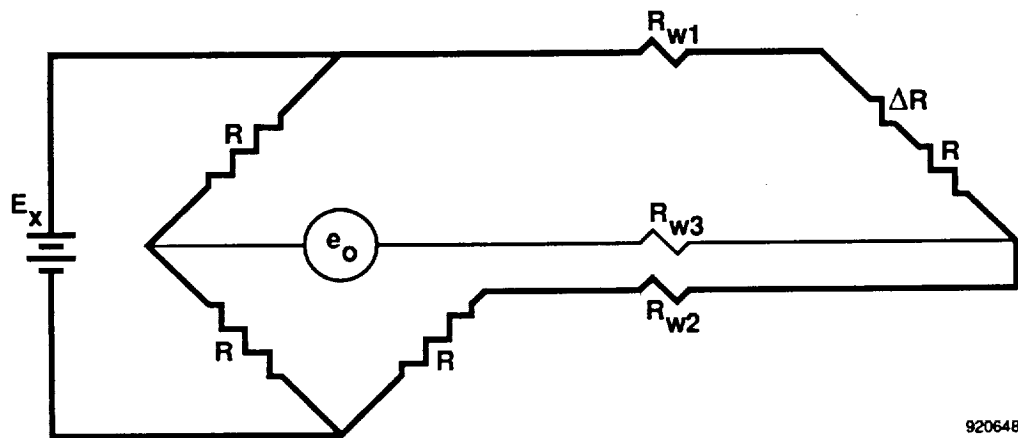

Figure 1. Single active arm Wheatstone bridge circuit.

The physical extension of the inner-bridge wiring of a Wheatstone bridge is often necessary in practice to measure the small change in a single remote resistance. In figure 1 these wires are modeled by their resistance, R_w. The lead wires to a remote bridge arm are arranged in the circuit of the figure

so that their effects subtract from each other in the bridge output by taking advantage of the analog computation characteristics of the circuit.

These advantages account for the broad popularity and wide use of this circuit in most areas of electrical measurements, especially the measurement of small changes in large resistances. Strain-gage signal conditioning is but one of many transducer applications of the Wheatstone bridge.

Disadvantages

Some disadvantages, however, appear when employing the Wheatstone bridge circuit for signal conditioning a single remote resistance transducer. In this situation, lead wires become an uncontrolled contribution to the measurement output that appears as a variable systematic error.

The Wheatstone bridge circuit has a long history of effective use, extending back to the earliest precision measurement of electrical resistance. Its advantages normally outweigh its disadvantages by a wide margin in most resistance measurement applications. This situation is believed to account for the absence of developments to overcome its disadvantages, especially the difficulty with ill-behaved lead wire resistances.

The subtractive properties of the Wheatstone bridge require equivalent currents to flow in opposite directions through resistances connected to a common circuit node. Such a circuit arrangement always includes voltage drops due to currents in lead wires connecting the resistances to the common node in the voltages being subtracted.

Lead wires to remote bridge arms always appear within the loop of the bridge as additional, variable resistances that desensitize the system. Lead wire resistances must be identical within 0.2 milliohms (mΩ) for their effects to sufficiently subtract in the bridge output and thereby avoid an observable output drift that is indistinguishable from a change in the gage resistance. Lead wire resistances are uncontrolled in the usual test environment, and the resistance variation is much larger in test situations involving high temperatures.

A single active arm Wheatstone bridge circuit always delivers an output voltage that is a nonlinear function of the resistance change in that arm. And each independent single active arm measurement requires three wires to tolerate even mild lead wire resistance variations. The following three equations illustrate these effects based on the circuit of figure 1:

Equation 1 is the Wheatstone bridge output from a resistance change in a single arm with zero lead wire resistance.

$$e_o = \frac{E_x}{4} \left(\frac{\frac{\Delta R}{R}}{1 + \frac{\Delta R}{2R}} \right) \tag{1}$$

The appearance of ΔR in the denominator of equation 1 causes the output to be a nonlinear function of ΔR.

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Equation 2 is the Wheatstone bridge output from a resistance change in a single arm with identical lead wire resistances, R_w, and additionally includes desensitization caused by identical lead wires.

$$e_o = \frac{E_x}{4} \left(\frac{\frac{\Delta R}{R}}{1 + \frac{R_w}{R} + \frac{\Delta R}{2R}} \right) \qquad (2)$$

The appearance of R_w in the denominator of equation 2 causes the output to be a nonlinear function of ΔR and R_w.

Equation 3 is the Wheatstone bridge output from a resistance change in a single arm with different lead wire resistances, R_{w1} and R_{w2}. This equation illustrates the major problem with lead wire resistance variation in high-temperature tests.

$$e_o = \frac{E_x}{4} \left(\frac{\frac{\Delta R + (R_{w1} - R_{w2})}{R}}{1 + \frac{\Delta R + R_{w1} + R_{w2}}{2R}} \right) \qquad (3)$$

The appearance of R_{w1} and R_{w2} in the numerator of equation 3 causes the output to be a direct function of their difference in addition to ΔR.

FOUR-TERMINAL VOLTAGE DIFFERENCE MEASUREMENT

The Wheatstone bridge uses a typical two-terminal voltmeter to indicate resistance changes. As discussed above, this approach has inherent limitations when lead wires are required in the bridge circuit arrangement. A new measurement approach is to use a four-terminal voltage difference measurement system. This permits measuring a voltage difference without including the voltage drops across wiring to the common connection found in the Wheatstone bridge configuration. The four-terminal voltage difference measurement is at the heart of the improved measurement results obtained with the constant current loop conditioning concept described in the following section.

CONSTANT CURRENT LOOP

The dominant electrical property of a series circuit is that the current is the same through all parts of the series circuit loop. This property is very useful when long lead wires must be used in a measurement circuit. The ubiquitous 4–20 milliampere (mA) current loop in industrial process control is one practical example of using this property of series circuits. A strain-gage signal conditioning circuit using a constant current loop and a voltmeter circuit with the above voltage difference measurement characteristics is now in operational use at the NASA Dryden Thermostructures Research Facility.

Theory of Operation

Figure 2 diagrams the concept and illustrates the theory that explains its operation for a single-gage resistance. The unique part of the approach illustrated in figure 2 is the four-terminal voltage difference measuring system. R_{w1} through R_{w4} are lead wire resistances with R_{w1} and R_{w2} carrying the constant excitation current I. The gage is modeled by an initial resistance, R, in series with its resistance change, ΔR. Note that if the sensing system for the voltage across the gage, V_g, has a sufficiently high input

impedance then no current will flow through R_{w3} and R_{w4}; therefore, no voltage drop will occur across them. R_{ref} is a reference resistor used to develop a voltage, V_{ref}, which is subtracted from the voltage across the gage, V_g.
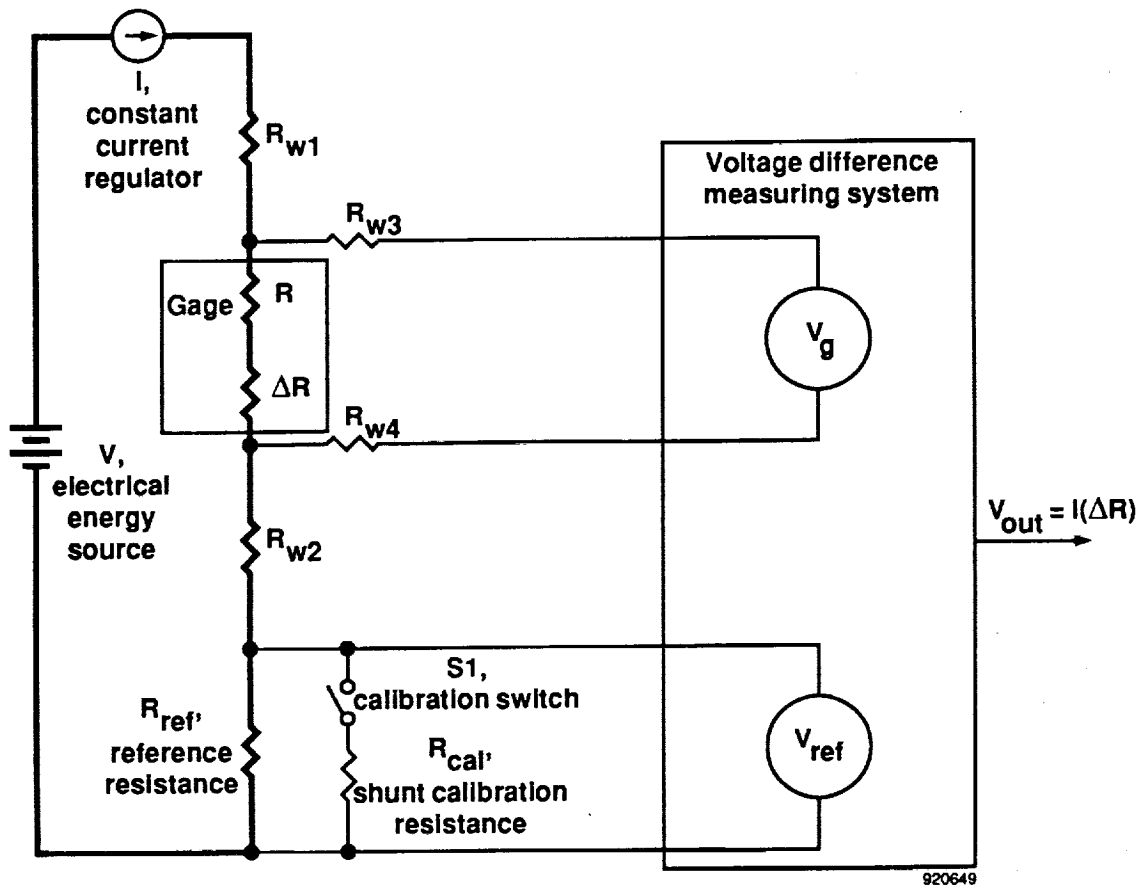

Figure 2. Current loop circuit for one-gage resistance.

The four-terminal voltage difference measuring system uses two terminals to sense V_g and two terminals to sense V_{ref}. Equations 4 through 6 model the circuit and illustrate the benefit of this four-terminal voltage measurement in a single constant current loop.

$$V_{out} = V_g - V_{ref} \tag{4}$$

$$V_{out} = I(R + \Delta R) - I(R_{ref}) \tag{5}$$

When $R_{ref} = R$,

$$V_{out} = I(\Delta R) \tag{6}$$

Note that R_w does not appear in the above equations.

When the voltage drop, V_{ref}, across a reference resistance in the current loop, R_{ref}, is subtracted from the voltage drop, V_g, caused by the same loop current I flowing through lead wires connected to a remote transducer resistance, R_g, the resulting output is equal to the difference in their resistances multiplied by the loop current. When their initial resistances are alike then the output is equal to the product of the current magnitude and the change in the transducing resistance, ΔR.

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The high impedance of the voltmeter draws insignificant current through R_{w3} and R_{w4}, the voltage sensing lead wires, so virtually no voltage drop occurs along these wires to include in the circuit model. Therefore, no lead wire resistance appears in the equation for V_{out}, and the circuit is theoretically insensitive to any lead wire resistance changes. Measurements, discussed later, confirm that lead wire resistances play no significant role in the output from a practical circuit implementation.

A small difference between the initial gage resistance, R, and the reference resistor, R_{ref}, will result in a correspondingly small output offset that can be subtracted out in data reduction as is also done with practical Wheatstone bridge circuits. This is a standard practice in strain-gage data reduction.

The maximum possible output voltage change per unit resistance change is achieved when using constant current excitation. By ignoring the second-order effects of the ΔR term in the denominator of the equation for the Wheatstone bridge output (equation 1), we have

$$e_O = \frac{E_x}{4}\left(\frac{\Delta R}{R}\right) \tag{7}$$

Since the E_x is $2V_g$ in a Wheatstone bridge circuit, the output in terms of the gage current and gage resistance change is

$$e_O = \frac{I(\Delta R)}{2} \tag{8}$$

Note that this is half the output available from equation 6, which describes the constant current loop output.

Advantages

The current loop has several major advantages as a resistance signal-conditioning circuit. The output bandwidth extends to dc. The loop performs a precise analog subtraction of only the desired voltage drops across the gage and references resistances while ignoring the undesired voltage drops across lead wire resistances in the current loop. Analog subtraction is independent of the loop excitation current. Its output voltage is a linear function of the remote resistance change and is double what a single active arm Wheatstone bridge delivers for the same gage power dissipation. Large changes in various lead or connector resistances have essentially no effect on the output of a practical circuit. It is optimized for observing small variations in large resistances. And, as explained later, a strain-gage rosette system requires only six wires.

Disadvantages

A significant disadvantage of this circuit is that four (rather than three) lead wires are required to connect single remote gage resistances. Strain-gage rosette measurements require fewer wires, however.

Another disadvantage is that the circuit is not electrically balanced. The impedance from each end of the gage to test article ground is not identical. This can be a concern because the useful upper frequency may be limited by its common mode rejection characteristics. This noise can result from the conversion of common mode energy to normal mode energy in the wiring from the gage to the signal-conditioning circuitry.

PRACTICAL CIRCUIT EXAMPLE

A practical means for accomplishing the function presented in figure 2 is illustrated in figure 3. The practical circuit in figure 3 uses a "flying capacitor multiplexer" circuit to subtract V_{ref} from V_g by transporting V_{ref} to another circuit location where it will directly subtract from V_g. This yields an output that is a function of only I and ΔR, because when the voltmeter draws no appreciable current, no lead wire resistances appear in the circuit equations.
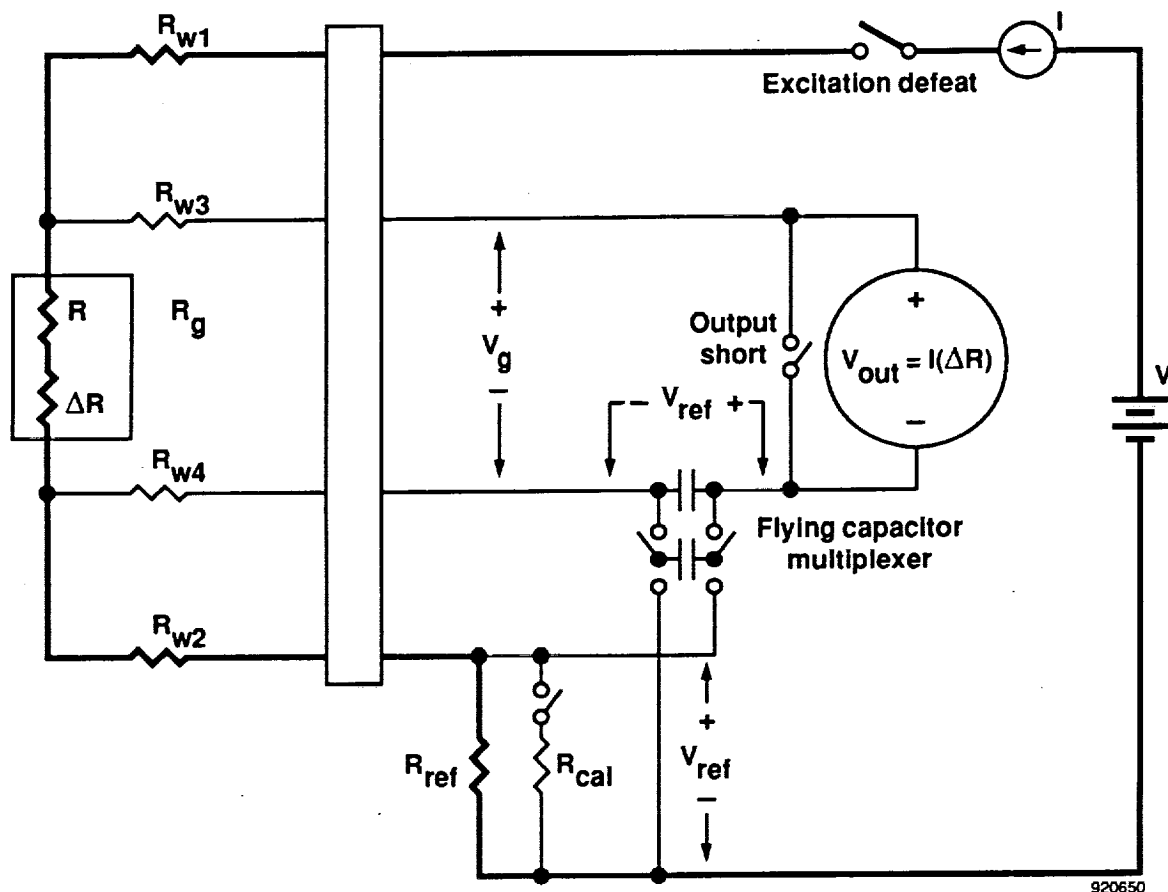

Figure 3. A practical current loop circuit for one remote gage resistance.

The flying capacitor multiplexer is only one of many possible means for implementing a four-terminal voltmeter that accomplishes the subtraction of two independent voltages regardless of what voltage exists between them. Commercially available switching components designed for flying capacitor multiplexers operate well in the up to 10-volt excitation levels needed for strain-gage work. Another advantage, discussed later, is the variety of analog computations possible in this manner, many that are beyond those available when using the Wheatstone bridge.

Circuit Features

The circuit in figure 3 includes a shunt calibration feature that operates in a manner equivalent to a shunt calibration with a Wheatstone bridge circuit. The resistance change that occurs as a result of

paralleling R_{ref} momentarily with R_{cal} appears in V_{out} as though it were caused by a positive ΔR of the same magnitude.

Because the current is the same in all parts of the loop (indicated by heavy lines in all figures), there is no need to parallel R_g to achieve a useful calibration. An R_{ref} is precisely known while R_g is difficult to assess in a Wheatstone bridge circuit, so the constant current loop is capable of a simpler and more reliable direct resistance calibration than a Wheatstone bridge.

An excitation defeat function (sometimes called power-off zero) is included in figure 3 to identify any active noise that may be entering the system. With the power-off zero activated, any extraneous noise from the installation environment may be identified and suppressed (if possible) to avoid contaminating the test data. The output short function is included in figure 3 to verify that no offset or common mode rejection problems exist in the voltmeter.

Circuit Component Requirements

The constant current source, I, should be stable to within less than 0.1 percent overall, have low output noise and, preferably, be both ohmically and electrostatically isolated from the power grid. As shown in equation 6, the magnitude of I directly affects the gain or sensitivity of the circuit. Constant current regulation is a common electronic function, so no detailed circuit is presented here. An insulated gate field-effect transistor is appropriate to use as a pass element in the constant current regulator to achieve the highest practical output impedance.

Accuracy and stability requirements for the components in figure 3 are the same as for similar components in traditional Wheatstone bridge circuits. R_{ref} and R_{cal} are the same components found as bridge completion and calibration components in Wheatstone bridge circuits. Resistances stable to within 10 ppm/°F with 0.1 percent precision are normally used. Temperature stability is the more important characteristic since the magnitude of any resistance component is easily measured for use in data reduction.

The flying capacitor multiplexer switches in figure 3 are analog multiplexer switches using field-effect transistors. They are commercially available with timing and drive circuitry all integrated into the same package and designed for use as an instrumentation building block. Switch leakage current should be under 10 nanoamperes (nA), on resistance less than 1000 Ω, and common mode rejection ratio greater than 100 dB.

The switching rate used to gather the experimental results, discussed later, was approximately 1000 samples/sec. This rate was chosen to achieve the lowest system noise floor with the specific multiplexer switches used in the circuit.

The capacitors in the circuit are nominally 0.1 or 1.0 microfarad (μF) metalized polypropylene film devices with low dielectric leakage. They are a type commonly used for sample and hold purposes. The magnitude of capacitance does not need to be either precise or stable since their only function is to transfer and store electrical charge with minimal loss. Since the capacitors remain charged to constant levels in operation, no significant current surges occur in the circuit and the signal-to-noise ratio is high for moderate bandwidths.

The calibration and output short switches are typically electromechanical switches or relays but field-effect transistor switches may be used if they have "on" resistances under 1 Ω and leakage currents under 10 nA. The calibration switch "on" resistance can be added to R_{cal} in calculating the response due to paralleling R_{cal} with R_{ref}.

The excitation defeat switch can be either an electromechanical relay or a transistor switch capable of carrying at least 30 mA. Power metal-oxide semiconductor field effect transistors (MOSFET's) having "on" resistances of under 1 Ω are suitable for this purpose. Excitation defeat can also be accomplished by programming the excitation current to zero.

The upper frequency limit of the circuit in figure 3 will be a function of the bandwidth of the constant current regulator; of the bandwidth of the voltmeter (the voltage drop, V_{ref}, across R_{ref} is constant); and of any electrical energy storage capability along the current loop.

Experimental Results

The circuit in figure 3 was used to gather data that demonstrates the sensitivity of its output to ΔR and its immunity to wide variations in the resistances of its lead wires. The tests involved extensive variations in both lead wire resistance (from 0 to 100 Ω) and gage resistance ΔR (from 0 to 5 Ω).

The following table summarizes the test results by presenting a limited set of data that cover the entire range of conditions tested. Data were reduced in terms of electrical resistance and microinches per inch (μin/in) of strain from a 120-Ω strain gage with a gage factor of 2. The ΔR is varied from 0 to 5 Ω in decades. The excitation current was 10 mA. The left column lists the input conditions in resistance change and equivalent microstrain ($\mu\epsilon$). The four right columns contain reduced data from voltage measurements using a bench top digital multimeter with 1.0-μVdc voltage and 1.0-mΩ resistance resolution. Offsets in the data set are all with respect to the initial indication with ΔR and all R_w values set to zero. The bottom section of the table lists the measured R_w resistances in the various lead wires to identify the test condition for that column.

The data in the table show that the circuit output is a reliable function of ΔR. Note that, unlike a Wheatstone bridge circuit, the lead wire resistances R_{w1} through R_{w4} are not identical. While they appear to be closely matched, in fact the variation in resistance among the four lead wires exceeds the normal output from a 120-Ω gage resistance's ΔR of about 0.5 Ω. Such lead wire variations in a Wheatstone bridge circuit would render its output indications completely useless. But with the constant current loop circuit, *any* single lead wire can be varied by 100 Ω or more with insignificant variation in the output indication.

The tolerance of the circuit to lead resistance changes means that almost any wire size or connector can be effectively used, even slip rings. Lead wires can be chosen to be large enough to survive in the test environment rather than as large as practical to minimize the negative effects of lead wire resistance in a Wheatstone bridge circuit. This will result in smaller and lighter wire bundles and connectors between the sensors and signal-conditioning equipment.

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Constant current loop signal-conditioning results reduced data for R_{ref} = 120.0 Ω.

ΔR Ohms	ΔR @ $R_w \approx 0\,\Omega$ Ohms	ΔR @ $R_w \approx 10\,\Omega$ Ohms	ΔR @ $R_w \approx 30\,\Omega$ Ohms	ΔR @ $R_w \approx 100\,\Omega$ Ohms
0.00	0.000	−0.002	0.000	0.004
0.05	0.050	0.049	0.050	0.054
0.50	0.500	0.499	0.500	0.504
5.00	4.998	4.997	4.998	5.002

Equivalent $\mu\epsilon$ $\mu\epsilon = \Delta R/(GF*R)$ μin/in	$\mu\epsilon$ @ $R_w \approx 0\,\Omega$ μin/in	$\mu\epsilon$ @ $R_w \approx 10\,\Omega$ μin/in	$\mu\epsilon$ @ $R_w \approx 30\,\Omega$ μin/in	$\mu\epsilon$ @ $R_w \approx 100\,\Omega$ μin/in
0	0	−6	0	16
208	208	204	209	225
2083	2084	2080	2086	2102
20833	20829	20827	20833	20849

Wire identification	Measured lead wire resistance			
	Ohms	Ohms	Ohms	Ohms
R_{w1}	0	11.237	29.113	100.256
R_{w2}	0	11.761	29.266	100.822
R_{w3}	0	11.351	29.400	100.375
R_{w4}	0	11.042	29.626	100.915

STRAIN-GAGE ROSETTE MEASUREMENTS

The same reference resistor voltage drop, V_{ref}, can be used as an input for more than one voltage difference function. This makes it practical to include more than one gage resistance in a single current loop with a corresponding reduction in the number of lead wires required.

Figure 4 illustrates three gage resistances, R_{g1}, R_{g2}, and R_{g3}, in a single loop. This configuration is applicable to the common technique of using a group of three strain gages installed near each other to estimate the magnitude and direction of principal strain. All the advantages of the constant current loop are obtained with only six lead wires, three fewer than required when using a Wheatstone bridge circuit for the same measurement requirement. This is made possible with a four-terminal voltage difference indicating system. One pair of terminals from each system is used to sense the voltage drop across its respective gage. The second pair of terminals from each system is paralleled to sense the voltage drop across the single reference resistor in the constant current loop.

Figure 5 is a practical circuit employing the constant current loop in a strain-gage rosette measurement application. R_{w3} through R_{w6} are used to sense the three independent voltage drops across each gage resistance. The three output voltages are developed by subtracting the same reference voltage from each of the three gage voltage drops. The performance of this circuit for each of the three gage resistances is equivalent to the single-gage circuit. Observe that the quantity of lead wires is equal to three *plus* the number of gages in the loop. Rosette measurements using Wheatstone bridge circuitry require a quantity of lead wires equal to three *times* the number of gages.
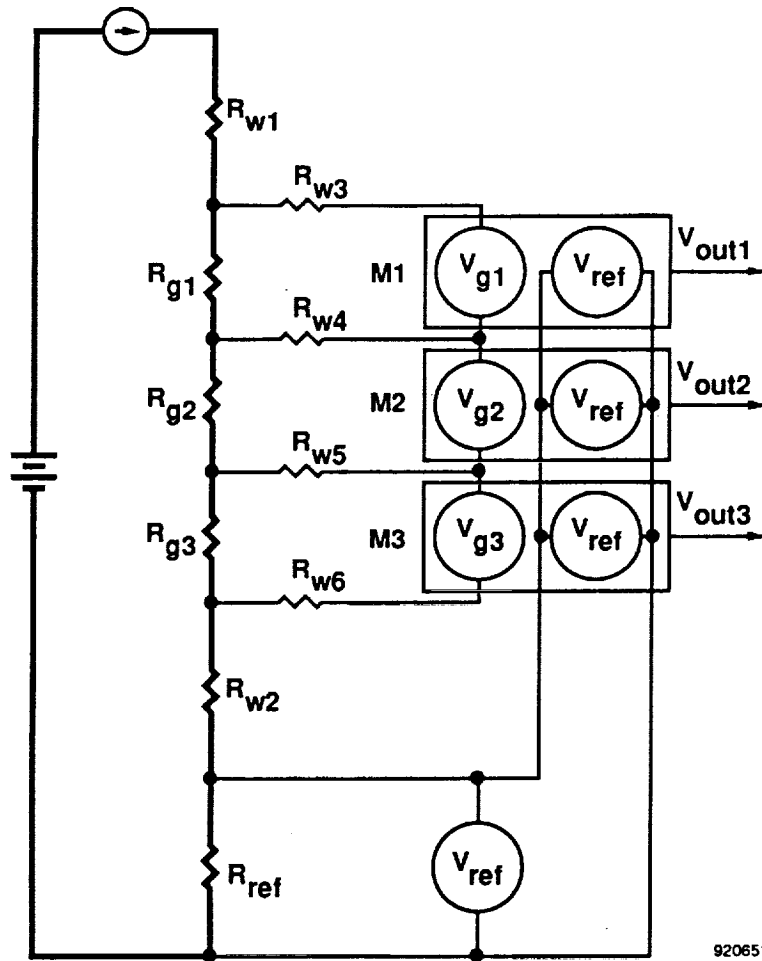
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Figure 4. Strain-gage rosette measurement using current loop signal conditioning with six lead wires.

In high-frequency applications, crosstalk may develop in the lead wires. This can result from the circuit impedances not being electrically balanced with respect to the test article ground potential.

The general approach discussed above can be adapted to other gage configurations. Apparent strain- and temperature-compensating resistances are often located near the gage resistance. The Hi Shear (ref. 6) and PdCr based high-temperature static strain gage (ref. 7) are examples of this need.

SIMULTANEOUS RESISTANCE AND TEMPERATURE MEASUREMENTS

Simultaneous resistance and temperature measurements can be made with an adaptation of the constant current loop circuit by using thermocouple wire for the lead wires that sense the voltage drop across a gage resistance. This is practical when a reversing rather than a unidirectional constant current excitation is used with appropriate signal processing.

An electronic double pole, double throw switch is used to reverse the current through a transducer that is excited by a dc constant current excitation source. By maintaining a constant current level while
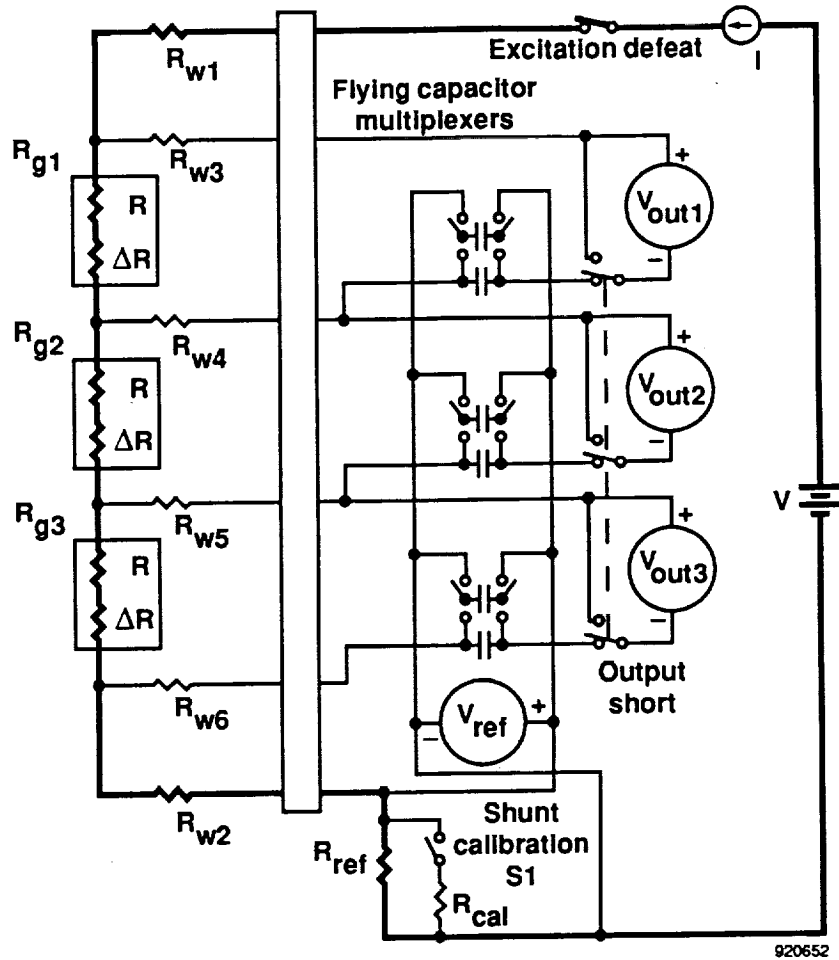
Figure 5. A practical strain-gage rosette measurement circuit using current loop signal conditioning with six lead wires.

reversing excitation direction, as indicated in figure 6, output voltages V_A and V_B are developed while the current is flowing through the gage resistance, R_g, as indicated by I_A and I_B, respectively.

When insignificant current is drawn while measuring voltages, the circuit equations for figure 4 are

$$V_A = +[(V+) + (V-)] + I(R + \Delta R) \tag{9}$$

$$V_B = -[(V+) + (V-)] + I(R + \Delta R) \tag{10}$$

for $R_{ref} = 2R$,

$$V_A + V_B - V_{ref} = 2I(\Delta R) \tag{11}$$

which derives gage resistance change and

$$V_A - V_B = 2[(V+) + (V-)] \tag{12}$$

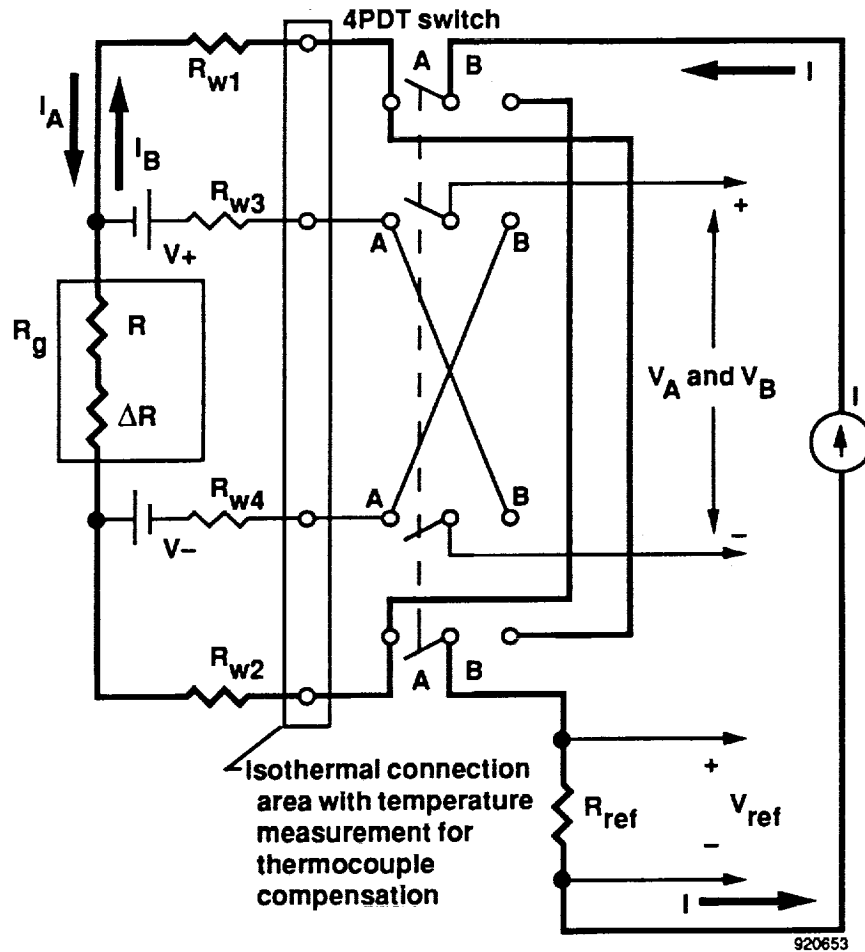which derives the thermoelectric (or other dc) voltage.

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Figure 6. Reversing constant current loop signal conditioning, which separates resistance changes and voltage outputs into independent data channels.

Equations 9 through 12 show how V_A and V_B, the sensing outputs, can be processed to yield nonself-generating transducer resistance change uncontaminated by lead wire and thermoelectric (or other dc) effects. They can also be processed to yield self-generating thermoelectric (or other dc) effects uncontaminated by transducer and lead wire resistance changes. Flying capacitor multiplexers, synchronized to capture and sum the various signals, have been successfully used to accomplish the arithmetic processing.

In this manner, four lead wires, including a pair of thermocouple wires, provide an output proportional to ΔR uncontaminated by lead wire resistance and thermoelectric effects. A separate output is developed that is proportional to the temperature of the thermocouple lead wire attachments to the terminals of the gage resistance. This is accomplished while preserving all the advantages of the direct constant current version except frequency response.

Regardless of the capabilities of the sensors, system frequency response will be limited by sampling theory to no greater than half the excitation current reversal frequency. In practice, several samples will be required to demultiplex the output in response to an input change, so the practical upper frequency response will be on the order of one-twentieth the excitation reversal frequency.

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CONCLUSIONS

A practical signal-conditioning circuit for resistance transducers identified as the constant current loop has been synthesized, analyzed and demonstrated. Theoretical predictions and laboratory results agree, demonstrating that the output provides dc frequency response, is unaffected by extremely large variations in lead wire resistance, and is inherently linear. The sensitivity is double that which a Wheatstone bridge delivers for the same power dissipation in the gage resistance.

Fewer and smaller lead wires are needed in multiple transducer installations, such as strain-gage rosettes, than for the Wheatstone bridge. An approach has been described that separates self-generating (such as thermoelectric) and nonself-generating (resistance change) effects into independent data channels by using alternating constant current excitation for the loop along with appropriate signal processing.

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