Practical Applications of Current Loop Signal Conditioning

Karl F. Anderson
Dryden Flight Research Center
Edwards, California

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Space Administration

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PRACTICAL APPLICATIONS OF CURRENT LOOP SIGNAL CONDITIONING

Karl F. Anderson
Measurement Systems Engineer
NASA Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523-0273

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ABSTRACT

This paper describes a variety of practical application circuits based on the current loop signal conditioning paradigm. Equations defining the circuit response are also provided. The constant current loop is a fundamental signal conditioning circuit concept that can be implemented in a variety of configurations for resistance-based transducers, such as strain gages and resistance temperature devices. The circuit features signal conditioning outputs which are unaffected by extremely large variations in lead wire resistance, direct current frequency response, and inherent linearity with respect to resistance change. Sensitivity of this circuit is double that of a Wheatstone bridge circuit. Electrical output is zero for resistance change equals zero. The same excitation and output sense wires can serve multiple transducers. More application arrangements are possible with constant current loop signal conditioning than with the Wheatstone bridge.

INTRODUCTION

The Wheatstone bridge circuit has a long history of successfully being used to measure electrical resistance and small changes in that resistance.[1] The variable resistance strain gage has used the Wheatstone bridge circuit in various forms for signal conditioning since its inception.[2] An adaptation of the Wheatstone bridge includes multiple constant current excitation sources within and external to the bridge.[3] A similar technique for minimizing the number of lead wires in multichannel strain measurements also exists.[4]

The constant current loop was developed to overcome the inherent difficulties of the Wheatstone bridge without the complexity arising from multiple excitation sources.[5] An extension of the concept provides the ability to simultaneously measure temperature and strain by using thermocouple wire to connect a variable-resistance strain gage to the signal conditioning circuitry.[6] The constant current loop is in daily use for strain gage signal conditioning at the NASA Dryden Flight Research Center.

This paper reviews the theory of the current loop paradigm and presents various possibilities for accomplishing the key voltage difference measurement function. Two loop current-regulation approaches are presented. In addition, a variety of circuit applications based on the current loop signal conditioning paradigm is described. Equations defining the circuit response is presented.

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

CURRENT LOOP THEORY

The current loop paradigm is a fundamental circuit concept that will operate with various electrical components and forms of excitation. Excitation possibilities include direct, alternating, and pulsed current. Inductance and capacitance measurements are possible with alternating current excitation. The various forms of excitation each have advantages that indicate their selection for use in certain applications and environments. For simplicity, direct current excitation and resistive components are used in the illustrations and equations presented in this paper.

SINGLE REMOTE GAGE RESISTANCE

Figure 1 diagrams the current loop signal conditioning paradigm and illustrates the theory that explains its operation for a single-gage resistance sensor. The unique part of the approach illustrated in figure 1 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 appreciable current will flow through R_{W3} and R_{W4}. As a result, no significant 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.

The four-terminal, high-impedance voltage difference measuring system of figure 1 uses two terminals to sense V_g and two terminals to sense V_{ref}. Equations 1 through 3 model the circuit and illustrate the benefit of this four-terminal voltage measurement in a single constant current loop.

$$V_{out} = V_g - V_{ref} \tag{1}$$

$$V_{out} = I(R + \Delta R) - I(R_{ref}) \tag{2}$$

When $R_{ref} = R$,

$$V_{out} = I(\Delta R) \tag{3}$$

Note that R_W does not appear in equations 1 through 3; therefore, V_{out} is theoretically uninfluenced by any R_W.

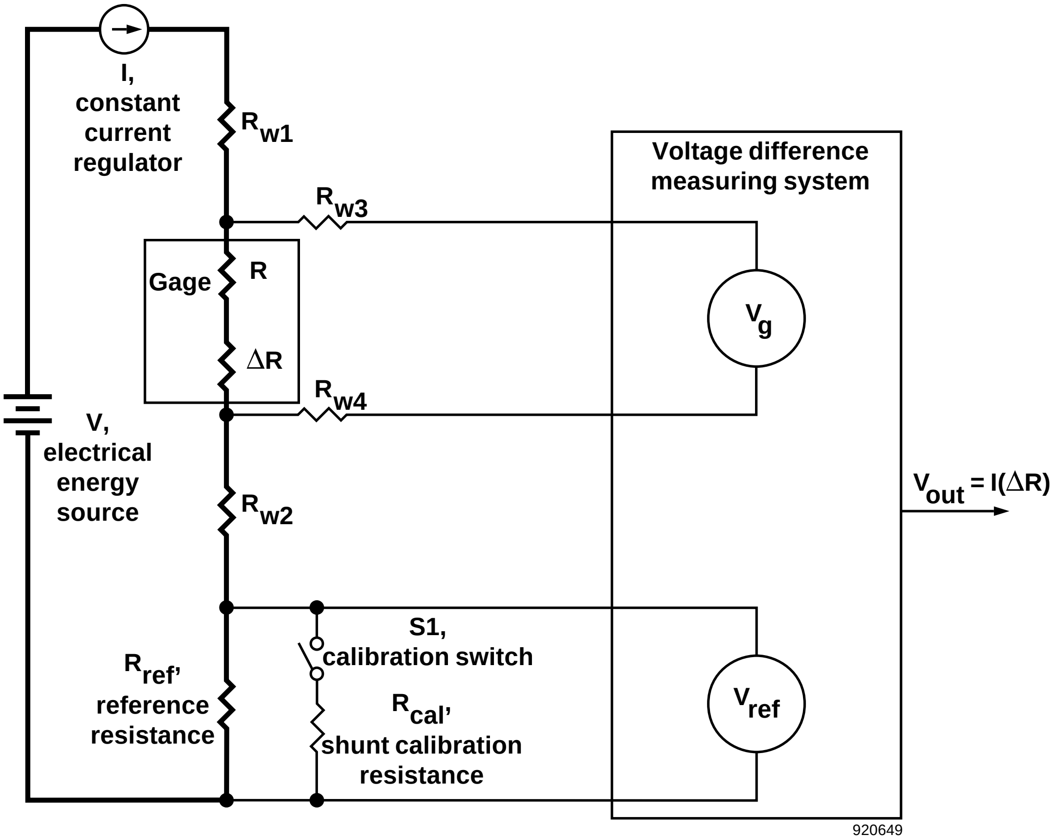

Figure 1. Current loop circuit for single-gage resistance.

A small difference between the initial gage resistance and the reference resistor will result in a correspondingly small output offset. This offset can be subtracted out in data reduction. This practice is standard procedure in strain-gage data reduction. Such subtraction is also commonly used with practical Wheatstone bridge circuits. The maximum possible output voltage change per unit of resistance change is achieved when using constant current excitation. Ignoring the second-order effects of the ΔR term in the denominator of the equation for the Wheatstone bridge output gives

$$e_o = (E_X/4)(\Delta R/R) \tag{4}$$

where e_o is the output, and E_X is the excitation for Wheatstone bridge circuits. Because the E_X is $2V_g$ in a Wheatstone bridge circuit, the output in terms of the gage current and gage resistance change is

$$e_o = I(\Delta R)/2 \tag{5}$$

Note that the output available from the Wheatstone bridge is one-half of the output available from the constant current loop output (eq. 3).

MULTIPLE REMOTE RESISTANCES

The same reference resistor voltage drop, V_{ref}, can be used as an input for more than one voltage difference function. This feature makes it practical to include more than one gage resistance in a single current loop. The key benefit of including multiple gages in the current loop is a reduction in the required number of lead wires.[5] To make apparent strain corrections, the reference resistance can be a gage resistance to achieve temperature compensation and arithmetic calculations. Refer to the Apparent Strain Corrections sub-subsection for additional details.

Figure 2 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

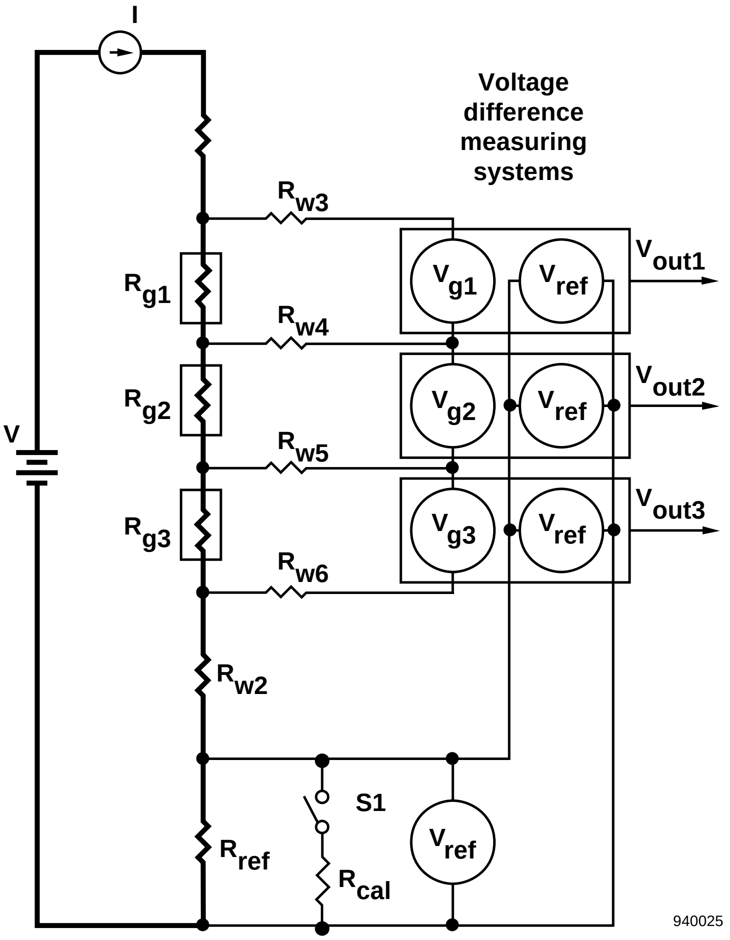

Figure 2. Strain-gage rosette measurement using current loop signal conditioning with six lead wires.

strain. The advantages of the constant current loop are obtained with only six lead wires. That is three wires less than are required when using a Wheatstone bridge circuit for the same measurement requirement.

VOLTAGE DIFFERENCE MEASUREMENT

The key function that makes possible the current loop paradigm is four-terminal voltage difference measurement. This measurement can be accomplished in many ways. The objective is to develop an output that is in direct proportion to the difference between two electrical potential differences. The resulting output must have appropriate stability and resolution for the intended application. Strain gage signal conditioning requires stability and resolution to within a few microvolts.

Several fundamental possibilities have been identified for accomplishing voltage difference measurement and are described in the following subsections. These possibilities develop a single potential difference output which is then observed with a conventional two-input voltmeter having suitable precision and stability. Other possibilities may also exist.

POTENTIAL TRANSPORT

A first potential difference can be transported from an inconvenient environment to another circuit location where it can be conveniently observed. This approach has found use in the “flying capacitor” multiplexer circuit.

Figure 3 shows a flying capacitor-based current loop circuit which uses this approach. In the development of the current loop concept, potential transport was the first approach identified which provided sufficient stability and resolution for strain gage signal conditioning. The V_{ref} is transported to appear across a capacitor in series with R_{W4}. Then, V_{out} is observed as the voltage difference between V_g and V_{ref}. This circuit includes switches to accomplish various calibration and data validity assurance functions. Excitation defeat, output short, and shunt calibration can be added to all circuit examples.[5]

CURRENT TRANSPORT

An electrical current can be modulated to carry information. This approach is used in the data current and current-summing amplifier circuits which are described in the following sub-subsections.

Data Current Circuit

A voltage difference measurement can be accomplished when a “data current” is routed through a load resistance located where its voltage drop can be observed in series opposition to a second voltage level. A conventional voltmeter then indicates the desired voltage difference.

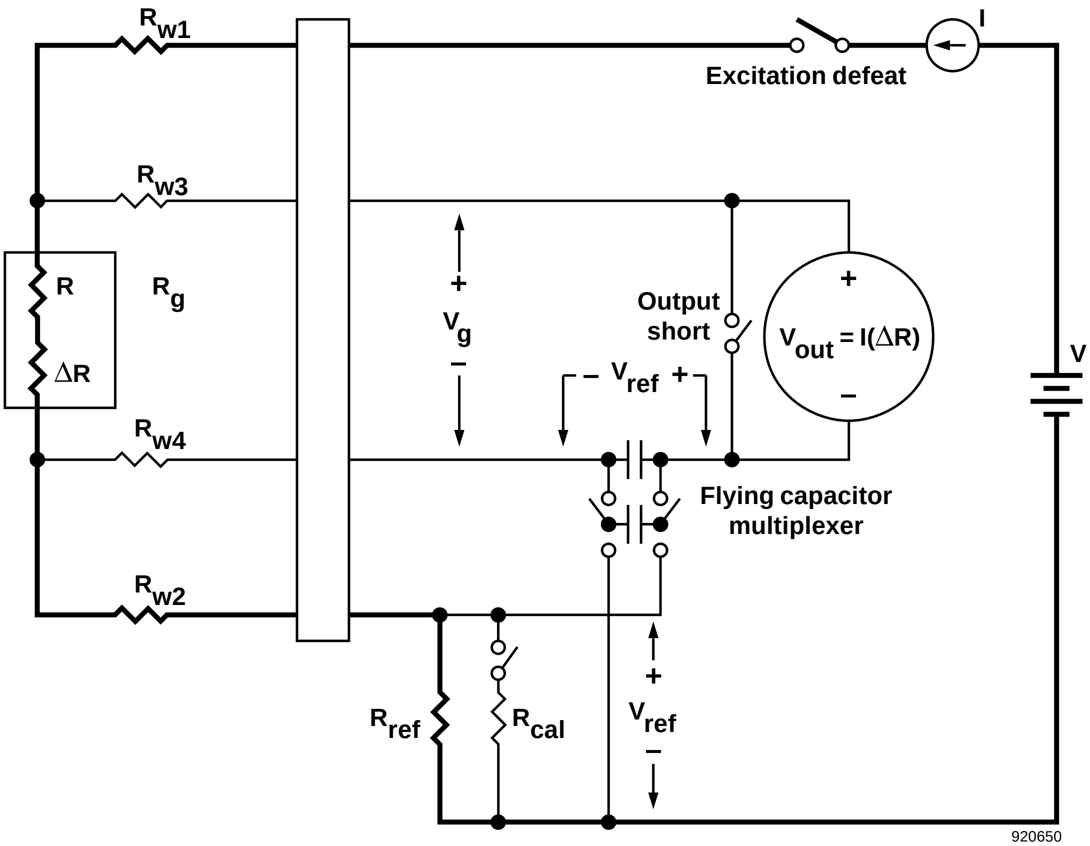

Figure 3. The flying capacitor circuit for developing a voltage difference measurement.

Figure 4 shows a current loop circuit using a data-current-based voltage difference measuring circuit. Here, the voltage developed across R_{d1} is caused to equal V_g by the operational amplifiers OA1 and OA2 and the current regulator pass element, Q1. This operation develops data current

$$ID = V_g / R_1 \tag{6}$$

Amplifier OA1 is connected to cause the voltage sensed through R_{W3} to appear at the top end of R_{d1}. The input of OA2 causes the voltage sensed through R_{W4} to appear at the bottom end of R_{d1} by turning on Q1 to cause the voltage drop across R_{d1} to equal V_g. The R_h provides a loop voltage drop to allow enough “headroom” to permit Q1, the data current pass element, to operate unsaturated.

The voltage drop across R_{d2} is equal to V_g when R_{d2} is equal to R_{d1}. The V_{out} is then the desired voltage difference between V_g and V_{ref}. Amplification is available in this circuit when R_{ref} and R_{d2} are proportionally greater than R and R_{d1}, respectively. The output of this circuit is

$$K = R_{ref} / R = R_{d2} / R_{d1} \tag{7}$$

$$V_{out} = K(V_g - V_{ref}) \qquad (8)$$

$$V_{out} = KI\Delta R \qquad (9)$$

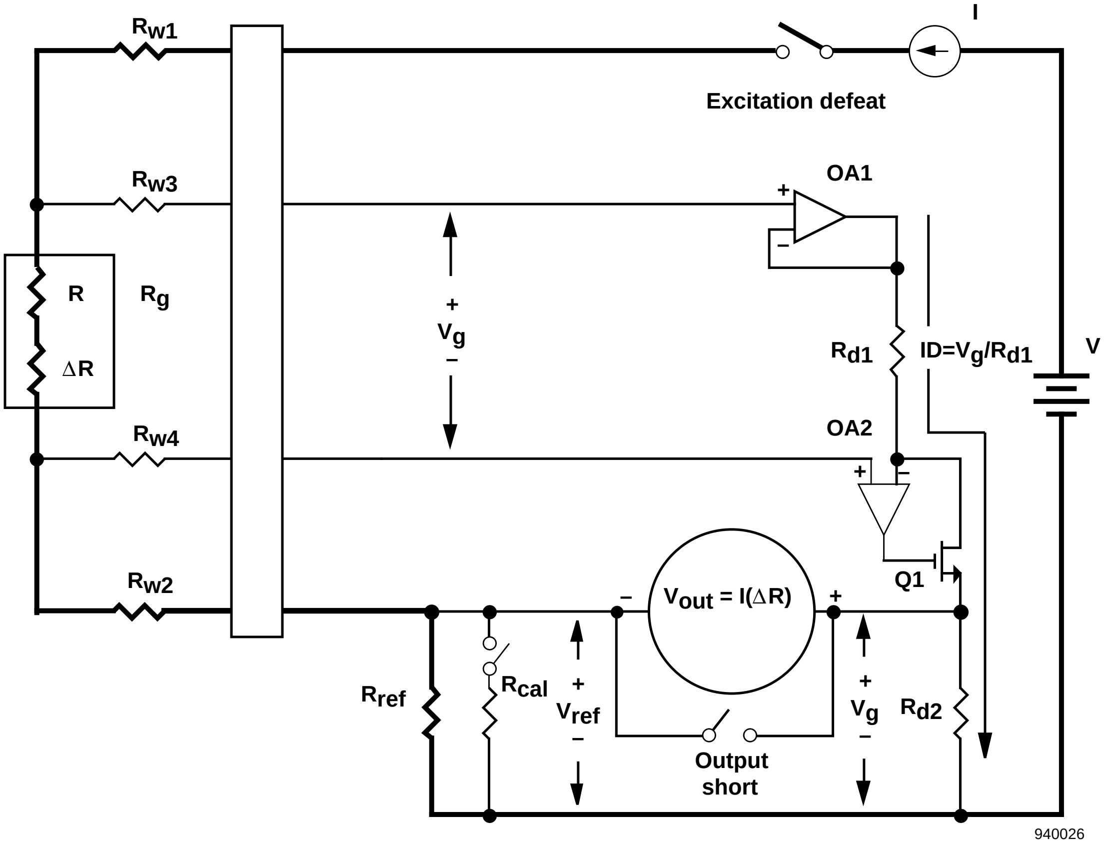

Figure 4. Data current circuit for developing a voltage difference.

Current-Summing Amplifier Circuits

Operational amplifiers connected to perform precision analog arithmetic can develop an output proportional to the difference in two input potential differences. The following subsections use a summing amplifier and an instrumentation amplifier as examples to illustrate these possibilities.

Summing Amplifiers–Figure 5 illustrates a classic analog subtraction circuit. This circuit uses operational amplifiers in a summing configuration to develop an output proportional to the voltage difference between two sets of floating inputs. Amplifiers OA1 through OA4 act as buffers to present a high impedance at their four inputs to the circuit nodes where the two voltage drops, V_g and V_{ref}, are sensed. Amplifier OA4 is unnecessary when its input is from a low-impedance point, such as a power supply output. Input summing resistances, R_i, and gain setting resistances, R_o, are each matched resistance sets. If the R_i resistors were directly connected to V_g and V_{ref}, then significant currents could be diverted from the current loop to the voltage difference measuring system, hence the need for buffer amplifiers OA1 through OA4. Absence of buffer amplifiers could cause the output to be unacceptably influenced by R_{W1} through R_{W4}. Amplification is available in this circuit in proportion to R_o/R_i. The output of this circuit is

$$V_{out} = (V_g - V_{ref})(R_o / R_i) \tag{10}$$

$$V_{out} = I\Delta R(R_o / R_i) \tag{11}$$

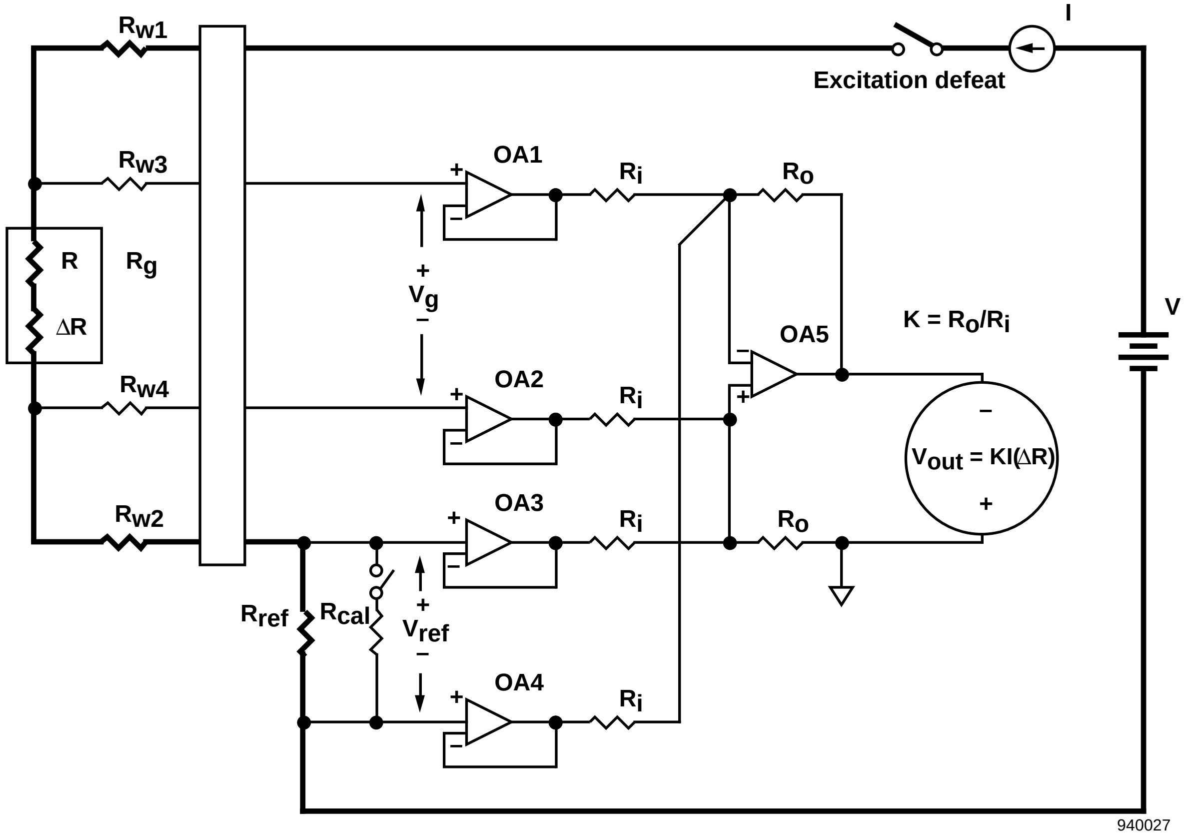

Figure 5. Operational amplifier circuit for developing a voltage difference measurement.

Instrumentation Amplifiers–Figure 6 illustrates subtraction by means of an instrumentation amplifier circuit. When operating at unity gain, an instrumentation amplifier produces an output voltage equal to the voltage difference between its input terminals. This output voltage is developed with respect to the point at which the output sense terminal is connected. By this means, the input level can be replicated at another point in the circuit to appear in series opposition to a second voltage. By connecting the sense terminal to the bottom of the reference resistor, the voltage between the instru-mentation amplifier output and the most positive end of reference resistor is $V_g - V_{ref}$, the desired voltage difference output. Gain is also available in this circuit when the instrument amplifier gain is adjusted to equal R_{ref}/R. The INA114 instrumentation amplifier is an appropriate choice for this purpose because of its low output referenced errors.

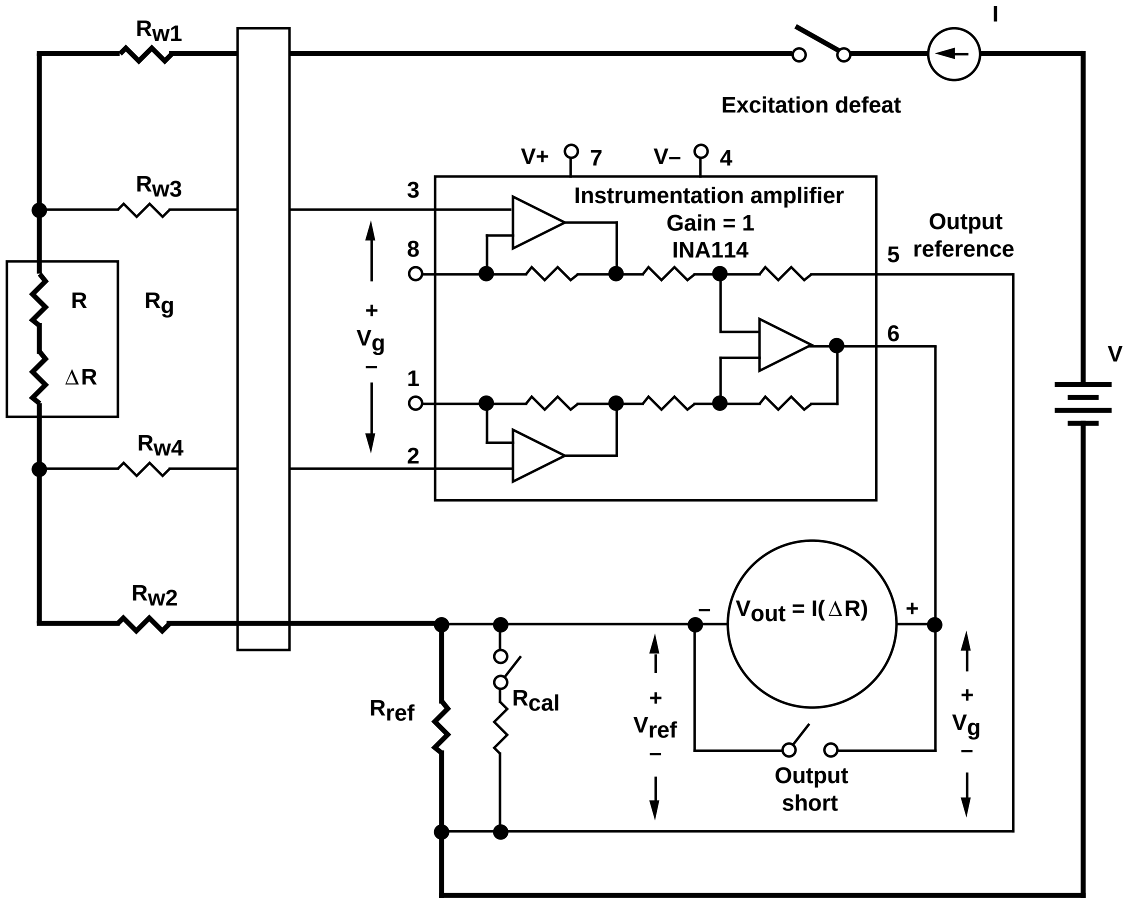

Figure 6. Instrumentation amplifier circuit for developing a voltage difference measurement.

CALIBRATION APPROACHES

A means for calibrating the overall measuring system end-to-end with respect to input resistance changes is a desirable operational feature. Fortunately, there is no need to parallel a remote R_g to achieve a useful calibration for sensitivity to individual loop resistance changes because current is the same in all parts of the loop. The circuitry carrying loop current is indicated by heavy lines in figures 1 through 14. If the desired output is the difference between two remote resistance changes, then paralleling one of these resistances may be necessary for a useful calibration. Calibration approaches for changing the reference voltage and gage current are described next.

CHANGING REFERENCE VOLTAGE

Figures 1 through 6 show a calibration circuit that changes the reference voltage by a predictable amount, ΔV_{cal}. This circuit consists of a calibration resistor, R_{cal}, which is electrically paralleled with the reference resistor, R_{ref}, while the calibration switch is closed. This connection reduces the apparent resistance of R_{ref} by ΔR_{cal} as calculated from

$$\Delta R_{cal} = R_{ref} - R_{ref} / R_{cal} / (R_{ref} + R_{cal}) \qquad (12)$$

For convenience in reducing strain gage data when $R_g = R_{ref}$,

$$\Delta R_{cal} / R_g = R_{ref} / (R_{ref} + R_{cal}) \qquad (13)$$

Because the same current, I, flows in all parts of the current loop, an apparent reduction ΔR_{cal} in R_{ref} appears in the system output as a voltage change, ΔV_{cal}, as though there had been an equivalent increase in R_g. Thus, R_{cal}, R_g, and R_{ref} define a reliable overall measurement system sensitivity factor when a change in system output is caused by paralleling R_{ref} with R_{cal}.

CHANGING GAGE CURRENT

Several new opportunities for circuit features develop when the voltage V_{ref} across R_{ref} is controlled to be constant in the feedback loop which regulates excitation current. As an example, figure 7 illustrates the change in excitation current, ΔI_{cal}, calibration technique.

The constant current regulator operates by forcing sufficient current through the loop to cause the voltage drop across R_{ref} to equal the reference source. This operation maintains the loop current at

$$I = V_{ref} / R_{ref} \qquad (14)$$

Connecting R_{cal} in parallel with R_{ref} causes a calibration current increment, ΔI_{cal}, to additionally flow in the constant current loop.

$$\Delta I_{cal} = V_{ref} / R_{cal} \qquad (15)$$

The output indication ΔV_{cal} is a function of the gage resistance R_g and ΔI_{cal}. Note that from the voltage difference measuring system perspective, ΔV_{cal} could have been developed by either a change in gage resistance, ΔR_{cal}, or by a change in excitation current, ΔI_{cal}. Equation 16 defines this equivalence.

$$\Delta V_{cal} = \Delta I R_g = \Delta R_{cal} I \qquad (16)$$

Substitution shows that

$$\Delta R_{cal} / R_g = R_{ref} / R_{cal} \qquad (17)$$

Note that the denominator of equation 17, which models the current change calibration, does not include R_{ref} as does equation 13 for voltage change calibration. By definition, strain is developed from resistance measurements by means of a gage factor, *GF*, calibration. That is,

$$GF(\text{strain}) = \Delta R/R \tag{18}$$

As a result, the strain simulated by a ΔI calibration is

$$\text{strain} = R_{ref}/(GF\,R_{cal}) \tag{19}$$

This result is interesting in that the data shift caused by paralleling R_{ref} with R_{cal} provides the system sensitivity to $\Delta R/R$ *without prior knowledge of* R_g.

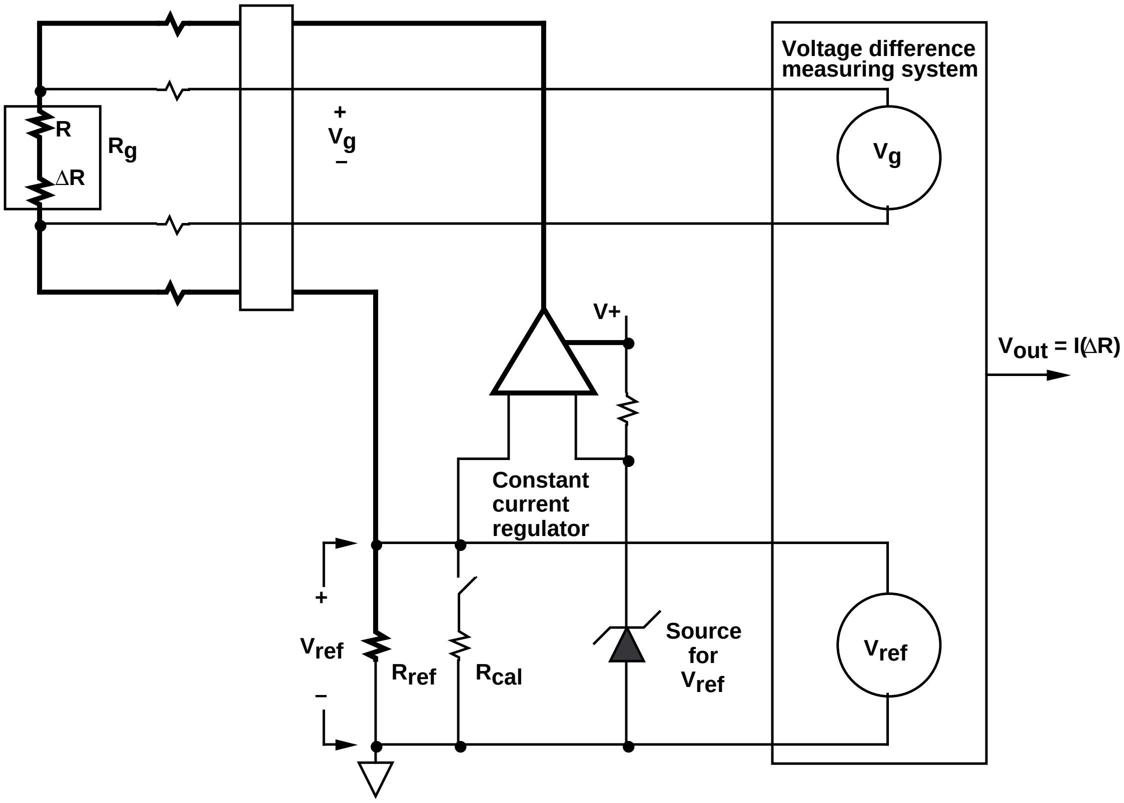

Figure 7. Current loop circuit with ΔI calibration.

Note that ΔI calibration involves precise currents flowing through R_{ref} and R_g. A small systematic error can exist when a ΔI offset adjustment circuit is also in use. This error is typically ignored, but it is simple to remove at the “balance” condition (zero electrical output from the voltage difference measuring system). In this situation, use the magnitude of R_g instead R_{ref} in equation 17.

OFFSET ADJUSTMENTS

Offset adjustments should be derived from the excitation current level. This derivation will cause excitation level variations to only result in percent-of-reading sensitivity errors rather than in additional percent-of-full-scale offset drifts. Adjustments for changing the reference voltage and gage current are described next.

CHANGING REFERENCE VOLTAGE

Figure 8 illustrates a ΔV offset adjustment circuit with ΔI calibration. The offset level is applied additively to the reference voltage before it is sensed by the voltage difference measuring system. This approach does not affect the level of calibration output from shunting R_{ref} with R_{cal}. Offset authority is established by the ratio of output-to-input offset amplification resistances, R_{oo} to R_{io}.

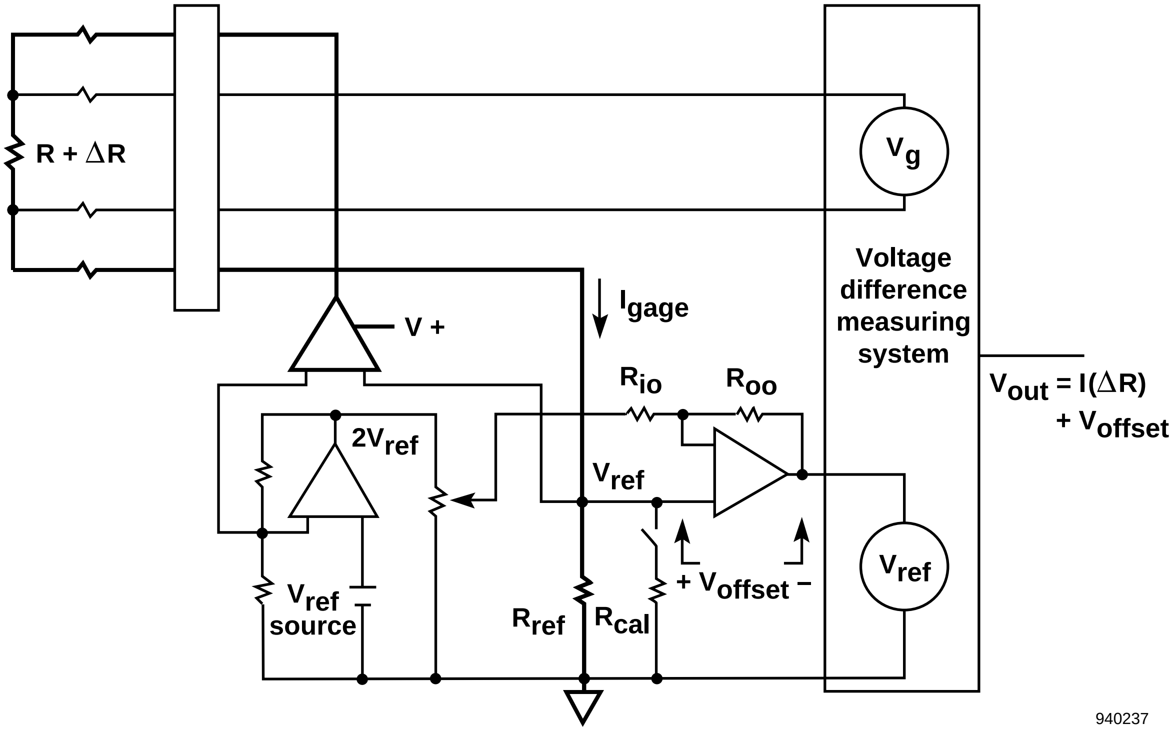

Figure 8. Instrumentation amplifier voltage difference circuit with reference voltage offset adjustment.

CHANGING GAGE CURRENT

Figure 9 illustrates a ΔI offset adjustment circuit. Magnitude of the offset adjustment is limited by R_{offset}. Resistor R_{offset} is connected between the positive end of V_{ref} and a potential V_{offset}, with a magnitude and polarity adjustable between zero and $2V_{ref}$. This circuit provides a variable bipolar offset current, $\pm I_{offset}$, which increases or decreases I_g.

$$\pm I_{offset} = \pm V_{offset} / R_{offset}) \tag{20}$$

The offset current is applied additively to the gage current, I_{gage}, to cause the gage voltage, V_g, to approach V_{ref}, the voltage drop across the reference resistor.

$$V_g = (I_{ref} + I_{offset})R_g \tag{21}$$

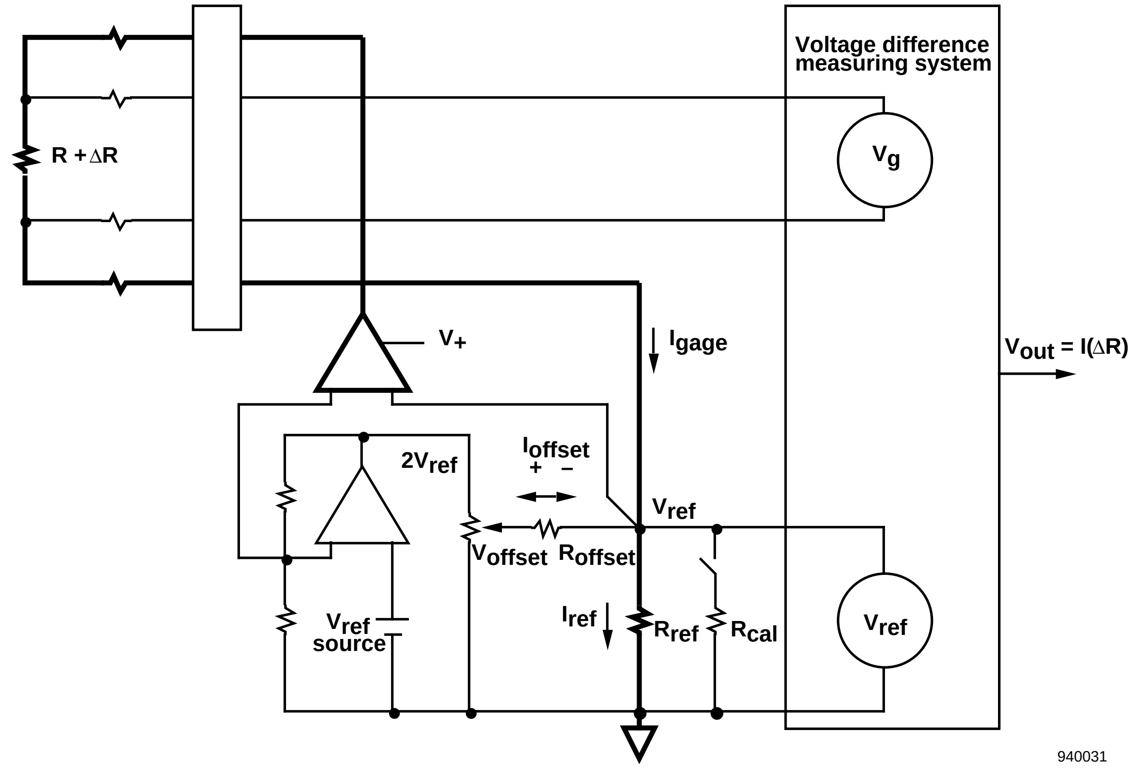

Figure 9. Current loop circuit with Δ*I* offset adjustment.

APPLICATIONS

Examples shown in figures 1 through 9 sense the voltage drop, V_g, directly across a gage resistance. This connection causes the output of current loop signal conditioning to be uninfluenced by any lead wire resistance as long as the voltage difference measurement system and the current regulator operate within their ability to reject common mode voltages and deliver a constant current to the set of resistances in the loop.

In addition, figures 1 through 9 provide separate outputs for each gage resistance in the current loop. Arranging two or more gages in a current loop circuit such that gage resistance changes add, subtract, or both, to develop a single output can be useful. Half- and full-bridge arrangements of the Wheatstone circuit combine gage outputs in this manner.[2] Constant current loop signal conditioning provides more analog computation opportunities than the Wheatstone bridge. The application examples that follow show how additional computations can be accomplished.

MINIMIZING CONDUCTOR QUANTITY

If lead wire resistances are consistent enough, then acceptable results may be obtained by using fewer lead wires. Three-wire connections to one-fourth- and one-half-bridge Wheatstone circuits always depend on consistent lead wire resistance.[2]

A single remote gage connected with three lead wires can be arranged to include the voltage drop of R_{w1}, gage voltage drop of V_g, voltage drop of R_{w2}, and reference resistor voltage drop of V_{ref}. This situation may require only three lead wires to accurately monitor a remote resistance change (fig. 10). All other benefits of current loop signal conditioning remain available in this situation.

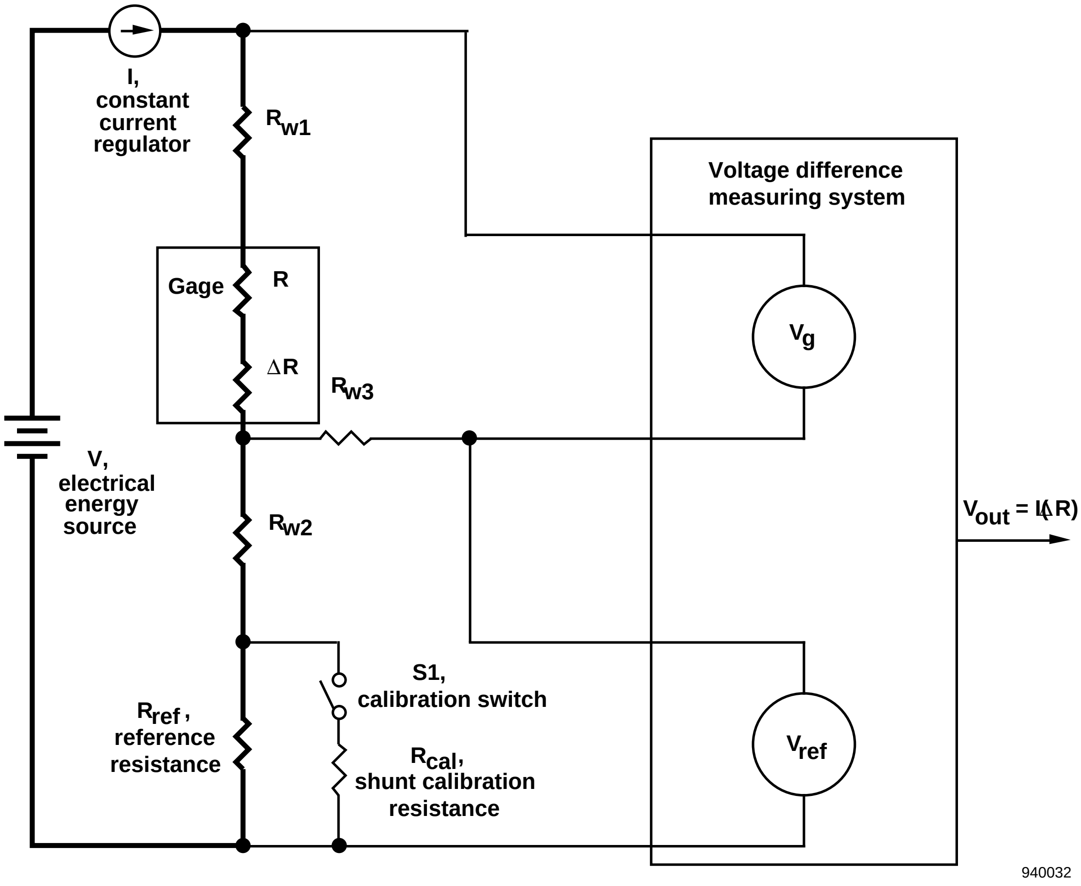

Figure 10. Three-wire connection to a gage.

The equations describing three-wire gage connections are

$$V_{out} = I\,[(R + \Delta R + R_{w1}) - (R_{ref} + R_{w2})] \qquad (22)$$

When $R_{W1} = R_{W2}$ and $R_{ref} = R$,

$$V_{out} = I(\Delta R) \tag{23}$$

This result is the same as equation 2. Lead wires with resistances that vary identically will induce no more than a constant offset in the output indication.

USING ANALOG COMPUTATIONS

Analog computations are possible in current loop circuits by including the voltage drops of additive gages in the direct (V_g) input and the voltage drops of subtractive gages in the inverting (V_{ref}) input of a voltage difference measurement circuit. In this situation, calibration by shunting a remote resistance in the circuit may be necessary. Shunting remote gage resistances through their sense lead wires is necessary because no “local” reference resistance is sensed by the voltage difference measuring circuit. Single and multiple loop computations are discussed in the following sub-subsections.

Single Loop

A variety of analog computations can be implemented within a single loop. These computations are accomplished by using one or more remote gages in a current loop to develop V_g, V_{ref}, or both. Note also that V_g for one voltage difference measuring circuit can be used as V_{ref} for another circuit. This feature makes the constant current loop an extremely versatile circuit for analog computations based on changes in remote gage resistances.

Apparent Strain Corrections–These corrections are accomplished by developing V_{ref} from the voltage drop across an “unstrained” gage in the same temperature environment as one or more strain-sensing gages. Figure 11 shows how apparent strain corrections are done without developing errors from lead wire resistances. Here, shunting R_{cal} across the remote unstrained gage provides a simultaneous calibration output for each of the strain-sensing voltage difference measuring systems.

Unlike the Wheatstone bridge, a single unstrained gage in a current loop can provide temperature compensation for several independent strain-sensing gages, for example, a strain gage rosette. This circuit minimizes gage and lead wire quantity in a circuit that is insensitive to lead wire resistance changes. If wire resistances R_{W1} and R_{W2} remain alike, then only three lead wires may be required.

Wheatstone Bridge Computation Similarities–Figure 12 illustrates how a set of four gages can be connected in a current loop such that their resistance changes add and subtract in a manner similar to Wheatstone bridge circuits.[2] Two gages comprise the additive and two gages comprise the subtractive voltage-sensing segments of the current loop. Note that any number of gages could have been included to expand the analog computation equation. When each gage has the same initial resistance, the output from this circuit is

$$V_{out} = I(\Delta R_{g1} + \Delta R_{g2} - \Delta R_{g3} - \Delta R_{g4}) \tag{24}$$

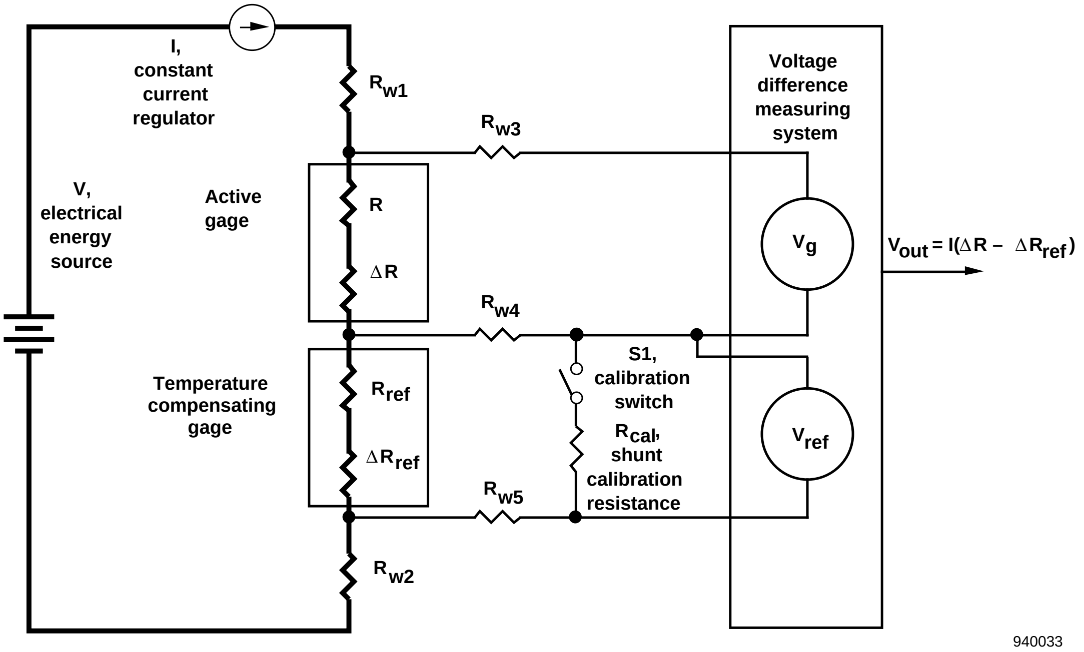

Figure 11. Temperature compensation using an unstrained gage for the reference resistance.

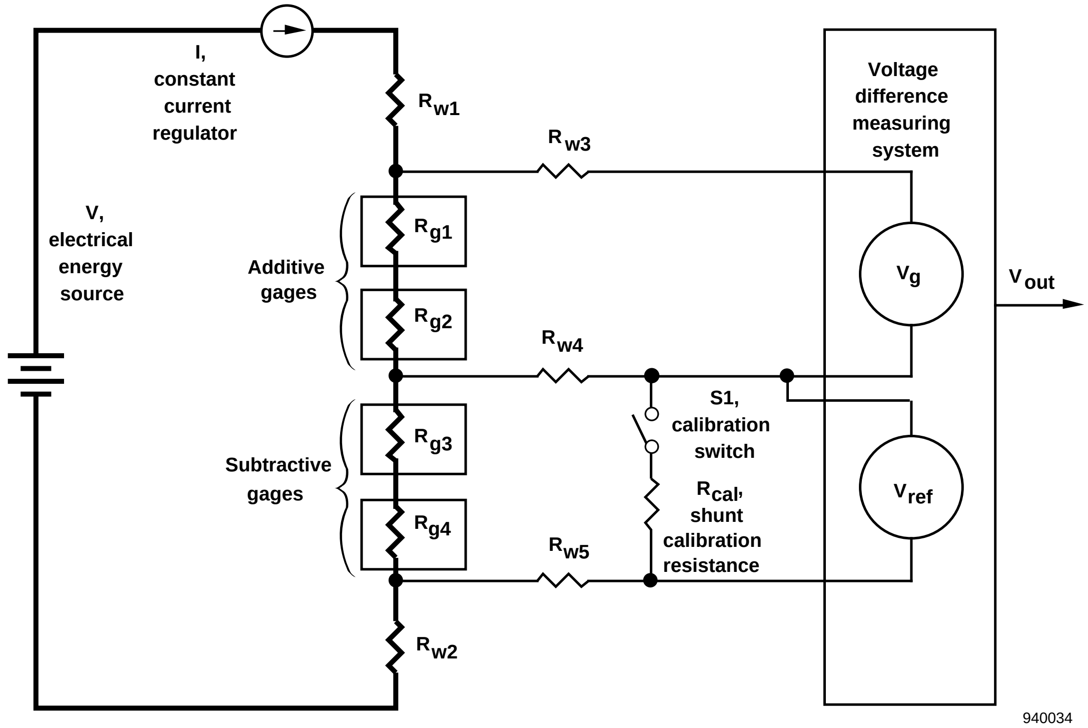

Figure 12. Analog computation using four gages.

Gage resistance labels in figure 12 do not reflect the adjacent positions they would have in a four-arm Wheatstone bridge arrangement. Resistance changes in opposite Wheatstone bridge arms are additive; such changes in adjacent arms subtract.[2] If R_{W1} and R_{W2} are sufficiently alike, then the current loop equivalent of the Wheatstone bridge can be achieved with only three lead wires.

Multiple Loops

Figure 13 illustrates how multiple current loop channel outputs can be combined to achieve a single output that is independently influenced by each current loop. This circuit accomplishes the calculations for combining measurement channels to implement loads equations.[7] The output from this circuit is

$$V_{out} = RF(V1/RI1 + V2/RI2 + V3/RI3 - V4/RI4 - V5/RI6 - V6/RI6) \qquad (25)$$

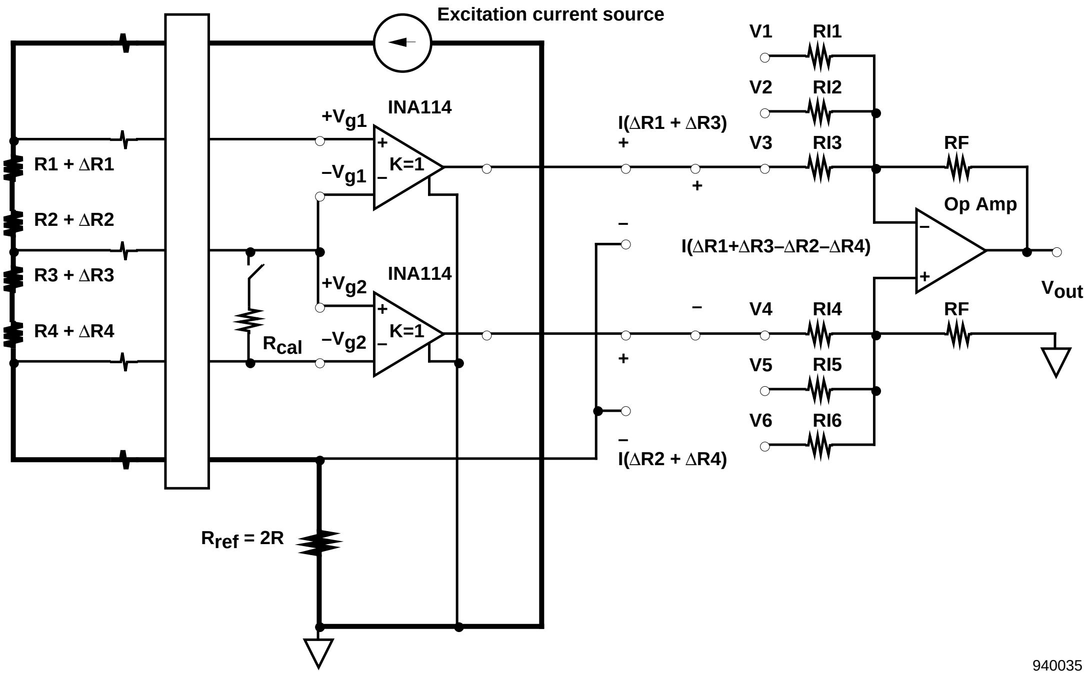

Figure 13. Multiple loop computation circuit.

MODIFYING EXISTING WHEATSTONE BRIDGE SYSTEMS

A substantial capital investment already exists in measurement systems that use Wheatstone bridge-based signal conditioning. Converting these existing systems to current loop operation is possible and practical.

Figure 14 shows a NASA-designed circuit modification to the existing Thermostructural Laboratory data acquisition system. This modification converts the signal conditioning from Wheatstone bridge to current loop by replacing the Wheatstone bridge completion and calibration circuitry. No other hardware or software changes were required to include current loop signal conditioning. All component values are identified. The designated INA114 instrumentation amplifier component is critical. The three operational amplifiers which it contains are essentially identical. As a result, this component has exceptionally low output-referred errors.

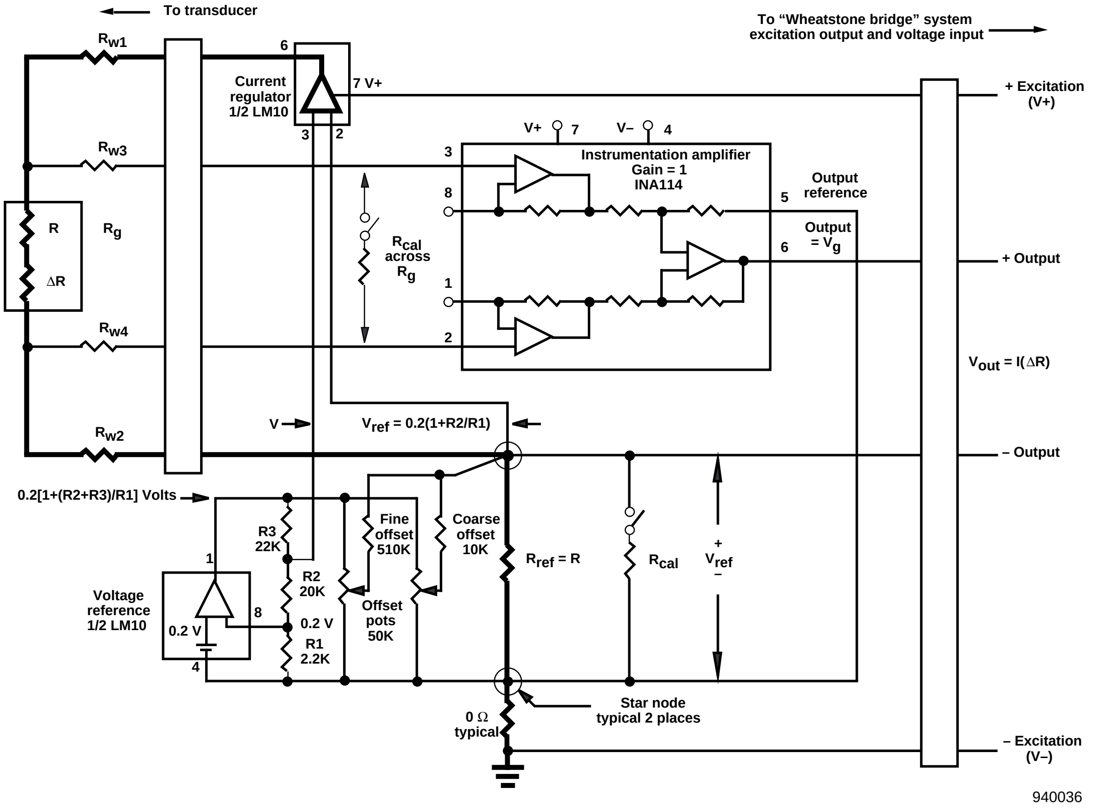

Figure 14. Modification to convert existing equipment from Wheatstone bridge to current loop circuitry.

CONCLUSIONS

The constant current loop is a fundamental signal conditioning circuit concept that can be implemented in a variety of configurations. Current loop signal conditioning circuits can be insensitive to changes in the resistance of any lead wire. The current change calibration identifies sensitivity to strain by developing an output that is directly proportional to the gage resistance at the time of calibration. Adapting existing Wheatstone bridge-based measurement systems to current loop operation can be practical. More application arrangements are possible using the constant current loop than using the Wheatstone bridge.

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