Triferential Subtraction in Strain Gage Signal Conditioning

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Introduction

The general form of NASA's Anderson loop measurement circuit topology invention depends on the dual-differential subtractor for its enabling technology.[1-9] This form of active subtractor tolerates random variations in lead wire resistance between the various strain gages in a loop as well as in lead wires and connections between a strain gage and its signal conditioning. However, many practical strain gage applications do not benefit from this level of sophistication because their strain gages are, in essence, electrically adjacent.

This paper presents a dual-differential subtractor definition and then presents a simpler triferential approach to active subtraction for strain gages that are electrically adjacent. Schematic diagrams for several configurations are presented. A triferential subtractor can be implemented with a single operational amplifier.

The Dual-Differential Subtraction Function

The dual-differential subtractor is a six-terminal, three-port active analog electronic circuit function defined in Fig. 1. The subtractor presents its analog output where it can be most usefully observed in the system. Subtractors typically deal with floating inputs and may provide either grounded or floating outputs.

The subtractor develops at its output port the difference between two selected (and possibly amplified) differential potential differences observed by its input ports. Different amplification factors can be used in observing the various loop potential differences and the loop can contain any practical number of observed impedances.

The ideal dual-differential subtractor delivers at its output, v_{out}, the difference between two input potential differences, v_1 and v_2, observed without energy transfer and amplified by gains A_1 and A_2, respectively. The output is uninfluenced by any common mode potential difference, v_{cm1} and v_{cm2}, or interior mode potential difference from one input to the other, v_{im}.

Observing Separated Strain Gages

The general theory underlying the Anderson loop combines an active, dual-differential subtractor (referred to as a “subtractor” for simplicity) with Kelvin sensing of observed potential differences across two (or more) impedances carrying the same current. The Anderson loop measurement circuit topology makes use of the dual-differential subtractor to provide the difference between the IR voltage drops across any two of potentially several different strain gage and reference resistance voltage drops (Fig. 2).

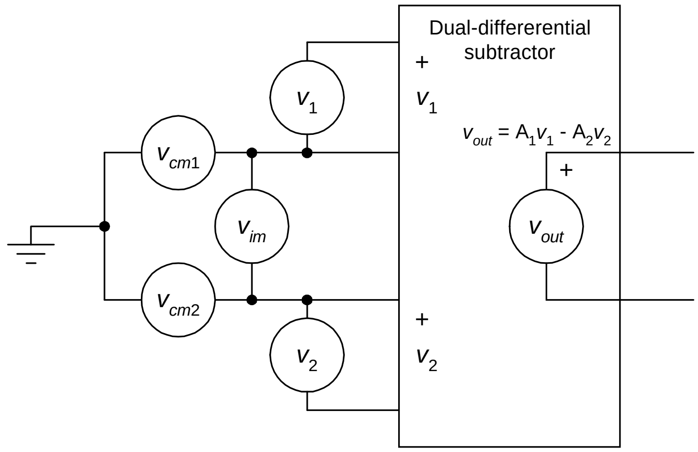

Figure 1, The dual-differential subtractor

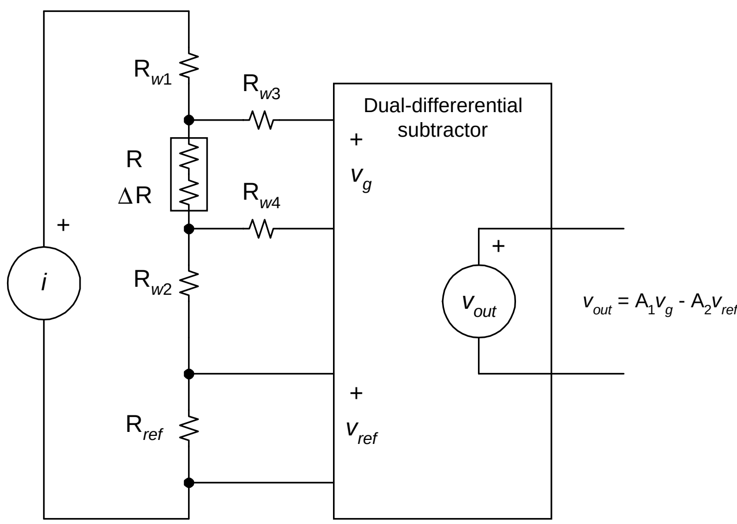

Figure 2, The Anderson loop measurement circuit topology

In practical applications, the input impedance of the subtractor's input ports is sufficiently high to develop an insignificant voltage drop across lead wire and connector resistances. So, the presence of typical and varying lead wire resistance is essentially irrelevant. The output of the circuit is given by:

$$v_{out} = A_1 v_g - A_2 v_{ref} \qquad (1)$$

R_{ref} becomes $R_2 + \Delta R_2$ when observing the voltage drops across two strain gages in an Anderson loop.

$$v_{out} = i\,[A_1\,(R_1 + \Delta R_1) - A_2\,(R_2 + \Delta R_2)] \qquad (2)$$

When $R_1 = R_2$ and $A_1 = A_2 = 1$, eq. 2 reduces to:

$$v_{out} = i\ (\Delta R_1 - \Delta R_2) \tag{3}$$

These equations model the measurement circuit for any reasonable resistance that may exist in the loop between strain gages, in sense wires and in their various connections.

Observing Adjacent Strain Gages

Resistances are electrically adjacent when they share a common circuit node. The common node is brought out through a lead wire that senses the more negative end of one strain gage also senses the more positive end of an adjacent strain gage or other circuit resistor. Strain gage pairs are typically wired using the standard three-wire configuration for bridge circuits and in either a three- or five-wire configuration for loop circuits.

All pairs of adjacent arms (including current-carrying lead wires) in a Wheatstone bridge are electrically adjacent resistances. Three examples of this concept are illustrated in Fig. 3. The five-wire configuration has the R_{w4} node common to both gages. The three-wire configurations have their R_{w3} node common to both gages. The resistance adjacent to the single gage configuration is a bridge-completion resistor in Wheatstone bridge signal-conditioning circuitry and the reference resistor in Anderson loop circuitry.

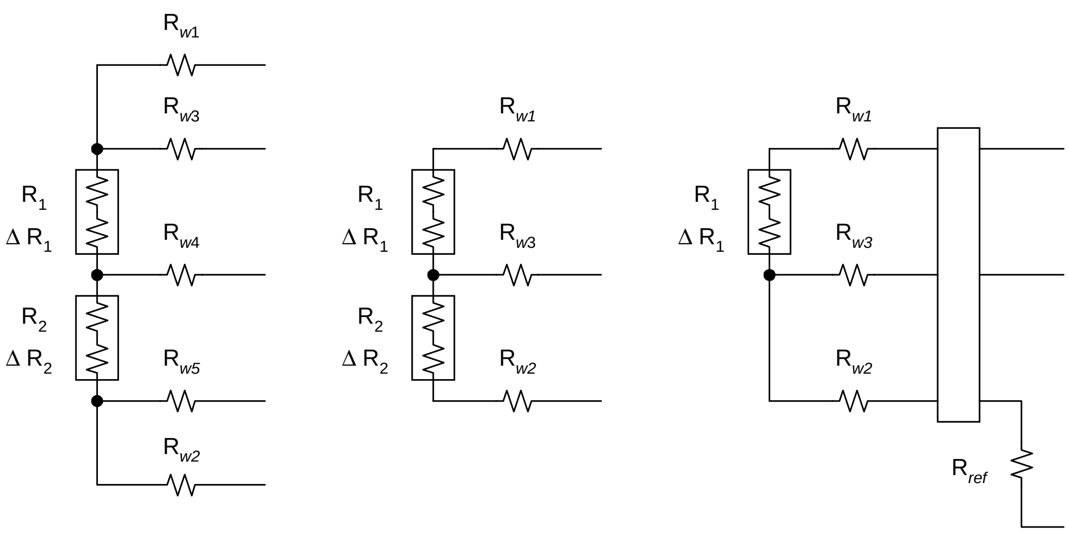

Figure 3 Adjacent-gage configurations

Circuits with three lead-wires start at the top with a gage plus a current-carrying lead wire, R_{w1}, electrically adjacent their R_{w3} connection to the common node. The common node followed by a circuit segment including R_{w2}, and either a second gage and a Wheatstone bridge completion or Anderson loop reference resistor. Of course, the order of the second resistance and R_{w2}, is dictated by the practical wiring situation, but it is electrically irrelevant.

With only three voltage-sensing wires arriving at the input to a signal conditioner there is a need for only three input wires to the four input terminals of a dual-differential subtractor. Accordingly, a special three input-terminal case of the dual-differential subtractor called a triferential subtractor has been developed.

Triferential Subtraction

The triferential subtractor develops at its output port the difference between two electrically adjacent (and possibly amplified) potential differences observed by its input ports. Different amplification factors can be used in observing the adjacent loop potential differences and the loop can contain any practical number of observed adjacent impedances.

The triferential subtractor is a five-terminal, three-port active analog electronic circuit function defined in Fig. 4. Triferential subtractors typically deal with floating inputs and provide ungrounded outputs that are observed differentially.

The ideal triferential subtractor delivers at its output, v_{out}, the difference between two adjacent input potential differences, v_1 and v_2, observed without energy transfer and amplified by gains A_1 and A_2, respectively. The output is uninfluenced by any common mode potential difference, v_{cm}.

The triferential subtractor is obviously a dual-differential subtractor with the interior-mode voltage, v_{im}, electrically shorted. For completeness, the definition was presented in its entirety. Equations 1, 2 and 3 describe the Anderson loop with either a dual-differential or a triferential subtractor.

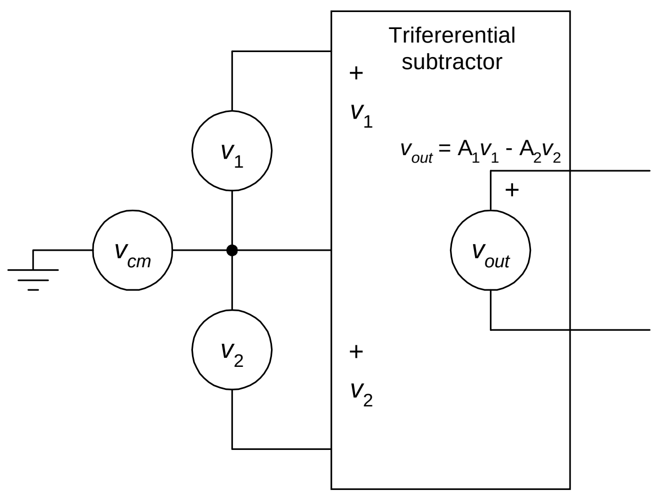

Figure 4, The triferential subtractor

Practical Implementations

Several implementations of the triferential subtractor have been developed. The user can consider the various system transfer function tradeoffs and select an approach optimum for the intended application. In general, having fewer amplifiers involved in subtraction will result in a correspondingly lower measurement noise floor and drift with temperature.

Single Operational Amplifier Design

The simplest triferential subtractor is implemented with a single operational amplifier (op amp) as illustrated in Fig. 5. It is a classic inverting operational amplifier circuit positioned to replicate its input voltage where it can be observed in series opposition to an adjacent loop voltage. There is a finite (but usually insignificant) current, i_{source}, drawn through the input resistance, R_{in}, and the balance network associated with the inverter.

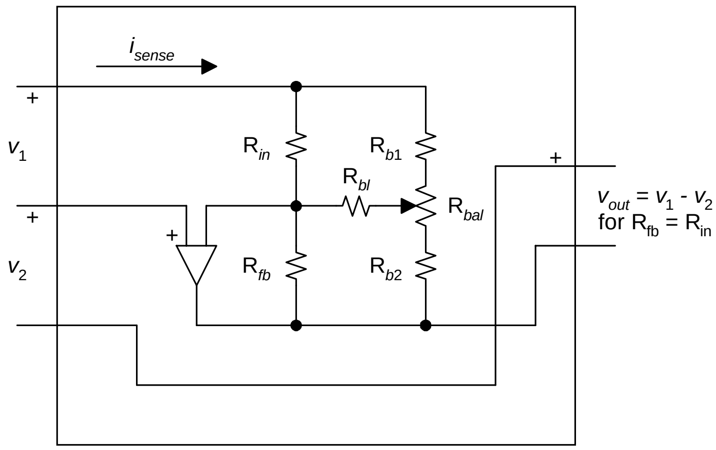

Figure 5, A triferential subtractor using a single operational amplifier

The input and feedback resistances, R_{in} and R_{fb}, respectively, are typically identical within component tolerances and selected to be an order of magnitude or two greater than the strain gage resistance. This minimizes drifts by keeping any lead-wire IR voltage drop due to the sense current, i_{sense}, from significantly altering the system output voltage.

The balance adjustment varies the A_1/A_2 ratio by trimming the R_{fb} / R_{in} ratio. Balance range resistors, R_{b1} and R_{b2}, and balance-limit resistance, R_{bl}, values are selected to achieve the desired balance authority by varying the amplifier gain around its nominal –1 value. This approach has the interesting effect at balance of developing an output signal linear in $(\Delta R_1 / R_1) - (\Delta R_2 / R_2)$. So it is not necessary to use strain gages that have essentially the same resistance.

It is not absolutely necessary to include R_{b1} and R_{b2}, but if they are omitted the balance limit resistance, R_{bl}, can become unreasonably large for fine adjustment of balance. Switching in different values of R_{b1} and R_{b2} can provide a high-resolution offset adjustment while removing a substantial initial offset.

A dual-gage five-wire signal conditioner using a single-op amp triferential subtractor is illustrated in Fig. 6. In all of the figures, R_{w1} carries the current from the excitation source to the gage(s). and R_{w2} returns this current to the reference resistor, R_{ref}. The voltage drop across R_{ref} is used as feedback for the excitation current regulator. The system's electrical sensitivity can be established by providing a calibration resistance at any of the indicated locations, R_{1cal}, R_{2cal}, or $R_{fb\ cal}$.

Bridge amplifiers can often supply the power to and amplify the low-level output from a triferential subtractor. By this means, existing Wheatstone bridge-based signal conditioning can be converted for Anderson loop operation, often by replacing the bridge completion and calibration card with either a dual-differential or triferential subtractor.

The classical approach for dealing with lead-wire resistance variations in bridge circuits is to cause a current-carrying lead wire to exist in adjacent arms of a bridge. These configurations also apply to wiring strain gages for triferential subtraction—with the added convenience that standard wiring color codes can be used. The three-wire single- and dual-gage configurations provide this feature. All of the benefits of current loop signal conditioning remain available except for tolerating random variations in any lead-wire resistance.

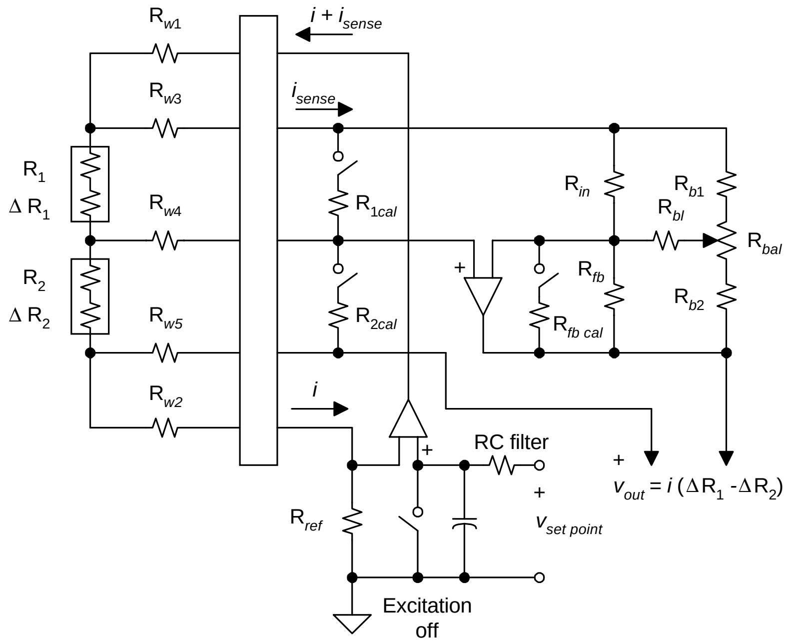

Figure 6, A dual-gage five-wire signal conditioner using a single-op amp triferential subtractor

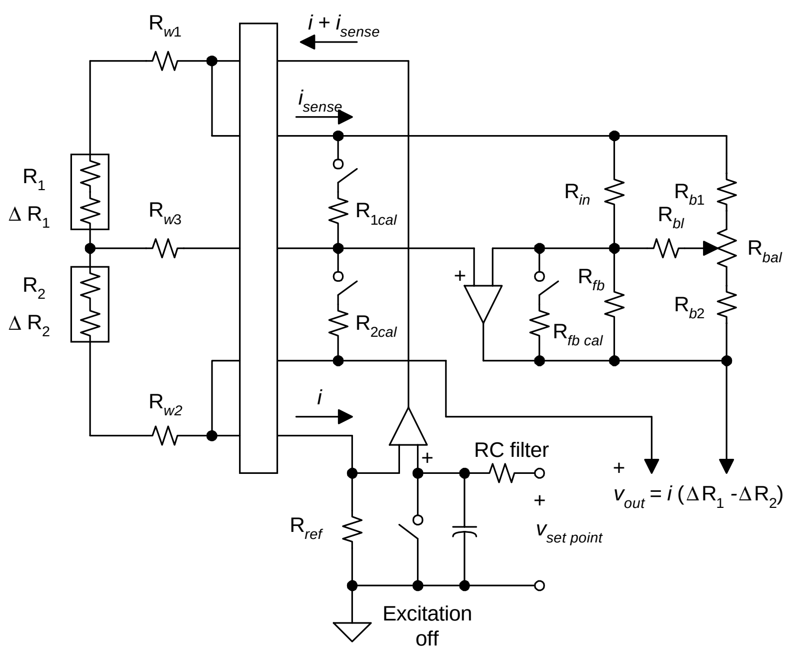

Figure 7, A dual-gage three-wire signal conditioner using a single-op amp triferential subtractor

A dual-gage three-wire signal conditioner using a single-op amp triferential subtractor is illustrated in Fig. 7. Note that i_{sense} is not a problem because it does not flow in a gage excitation wire.

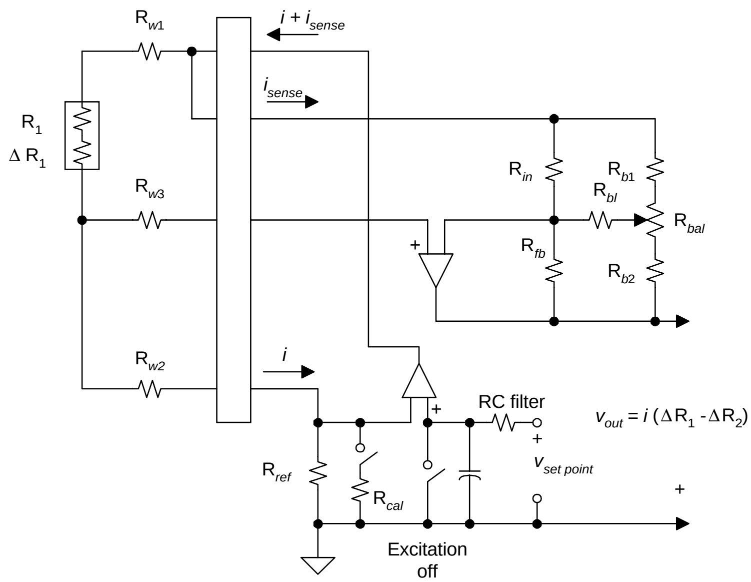

Figure 8, A single-gage three-wire signal conditioner using a single-op amp triferential subtractor

The three-wire technique for connecting a single strain gage is illustrated in Fig. 8. In this case, the reference resistor, R_{ref} and R_{w2} become the electrically adjacent resistance to the strain gage and R_{w1} resistance.

Note that the calibration resistance, R_{cal}, shunts the reference resistor, R_{ref}, to provide for ΔI calibration. This approach also has the interesting properties of providing common-mode rejection that does not require resistor matching and the output is single-ended with respect to analog common.

The sense current, i_{sense}, can become essentially irrelevant whenever voltage drop due to the sensing current through its lead wire is sufficiently small. Also, note that the strain gage excitation current, *i*, is regulated *after* any sensing current has been extracted from the loop.

Multiple Operational Amplifier Designs

A sense current can be reduced to near zero if its signal line is buffered by adding a unity-gain amplifier. The buffer amplifier can also contribute to providing a driven shield for the lead-wires from strain gages to the subtractor input. Several approaches using more than one operational amplifier follow.

Dual Operational Amplifier Designs

A buffered triferential subtractor with balance control and driven guard is presented in Fig. 9. It is often convenient to use two operational amplifiers in the same integrated-circuit package.

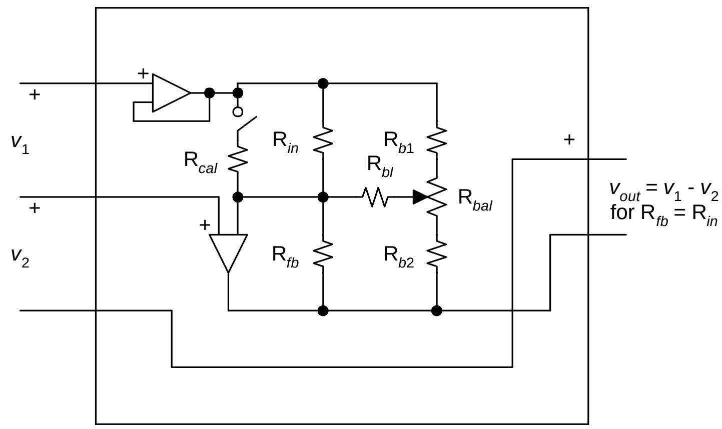

Figure 9, Buffered triferential subtractor

The addition of the unity-gain buffer amplifier reduces the current in its lead-wire to essentially zero. This assures that this lead-wire resistance has no appreciable effect on the circuit output. A cost of this feature is the additional drift and noise injected by an additional amplifier in the signal path.

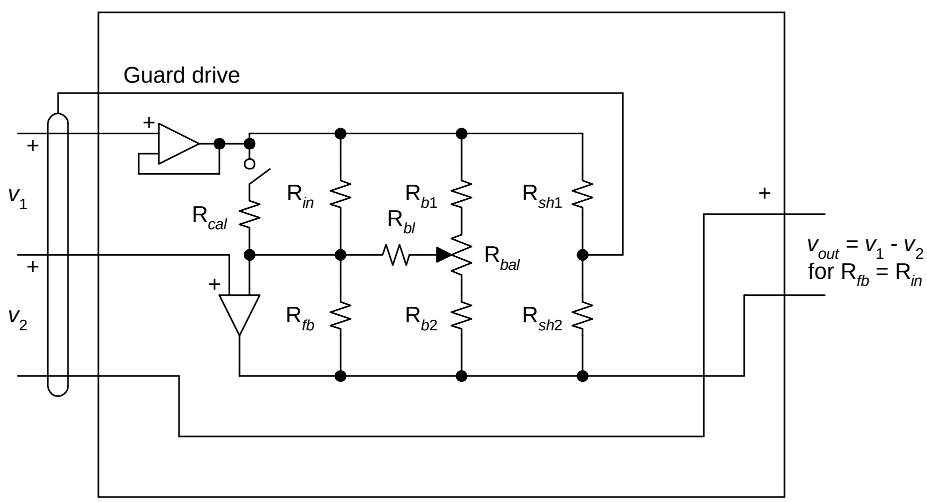

Figure 10, Driven guard from a buffered triferential subtractor

The unity gain buffer and inverting amplifiers have a low-impedance output that is close to the extremes of voltage across the triferential input. The current-limiting divider in Fig. 10 provides a convenient source of guard drive for the input lead-wires.

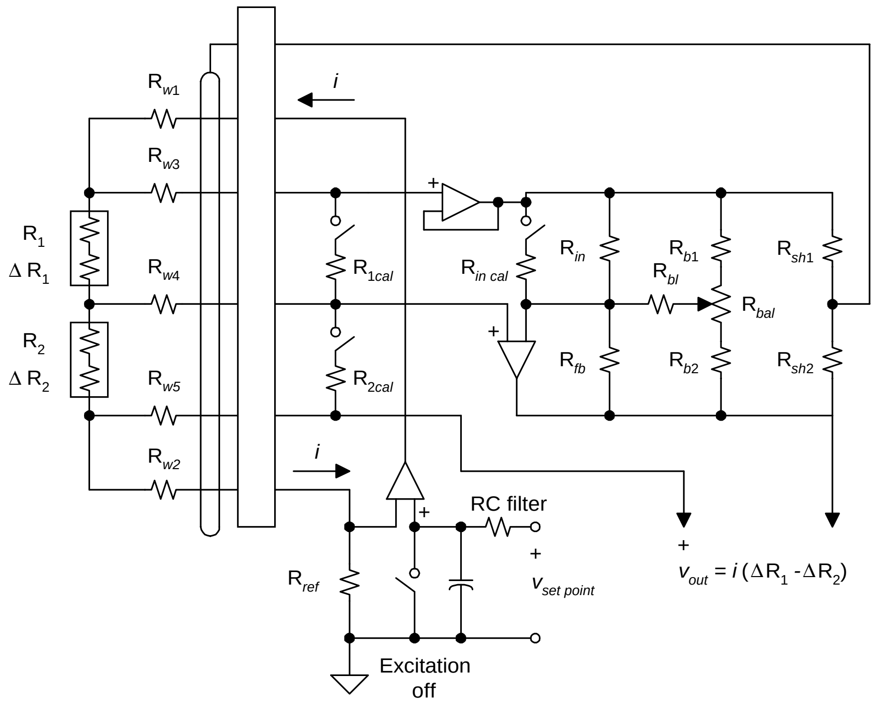

Figure 11, A dual-gage five-wire buffered triferential signal conditioner

A buffered triferential signal conditioner with guard drive is presented in Fig. 11. It illustrates a five-wire connection to two strain gages.

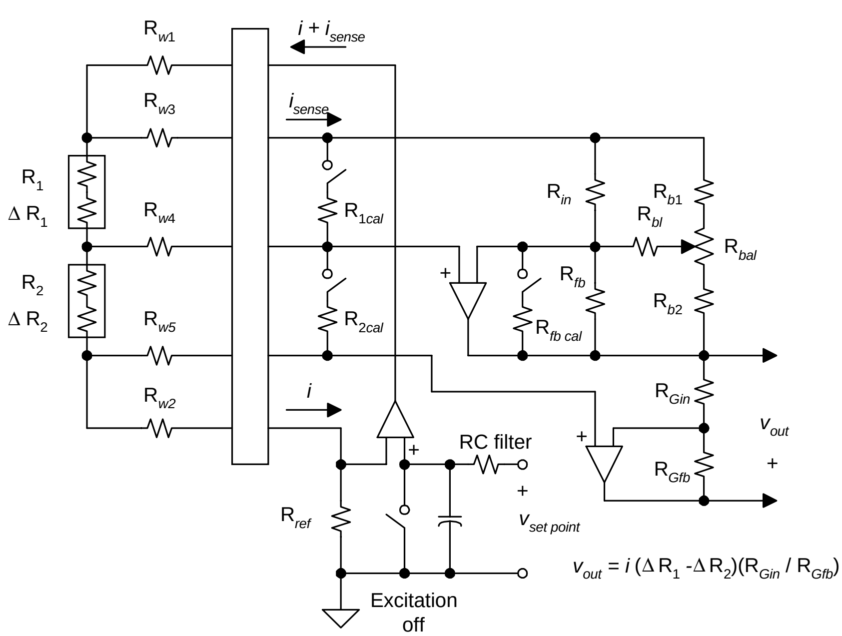

Figure 12, Amplification of a triferential signal conditioner output

The output of triferential subtractors can be amplified by using one more operational amplifier to provide a high-level differential output. Illustrated in Fig. 12, the additional gain is proportional to the ratio of R_{Gfb} to R_{Gin}.

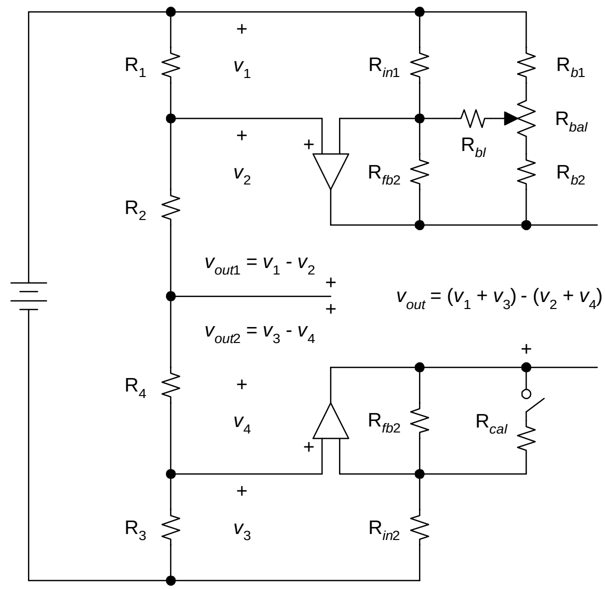

Figure 13, The dual-triferential subtractor

Another implementation of the triferential subtractor operates with four gages. Illustrated in Fig. 13, a triferential subtractor pair provides a differential signal that can be accepted at the input of most conventional dc Wheatstone bridge signal conditioning equipment. Resistors (not shown) added in series with the output lines can simulate the output impedance of a Wheatstone bridge. An unusual feature of this configuration is that a lead-wire is not required from the node at the mid-point of the strain gage group unless each "half-bridge" is to be observed independently.

Component Selection

Nearly all of the components involved in triferential subtractors are processing low-level analog signals. Therefore, it is essential to select components having suitable stability, noise performance and common-mode rejection. Resistors involved in subtraction should be selected with as much attention to their temperature coefficient of resistance as if it were a bridge completion resistor. The resistors that establish the guard drive potential and limit the guard current do not need to be particularly precise or stable because they do not contribute directly to the subtraction function.

Operational amplifiers should be selected primarily for low offset voltage changes with respect to temperature, for low noise at the input resistance they experience, bandwidth and input offset current. Chopper-stabilized operational amplifiers are recommended to achieve the best drift performance. Remember, micro-volts count.

Measurement Validity Checks

Competent engineering of measurement systems always involves providing means to document the validity of acquired data. Within the signal-conditioning circuitry, the most useful features for this purpose are an excitation zero and a means to identify the overall transfer function of the electronics. Circuitry to accomplish these functions is included with each signal conditioner figure.

Excitation can be reduced to essentially zero by causing the current regulator's set-point to become zero. This approach has the advantage of not driving the current regulator's operational amplifier into saturation by opening the current feedback loop. Always beware that removing excitation from strain gages upsets the thermal equilibrium of the gage-test article system. You may need to wait until thermal equilibrium is reestablished before continuing with the test.

The transfer function of the electronics can be accomplished by momentarily shunting a remote gage with a shunt calibration resistor connected via the sense lead-wires. Another method is to shunt either the input or feed back resistor in the triferential subtractor. The response to this calibration action can be easily related to an equivalent strain in a gage.

Summary

Anderson loop strain gage signal conditioning does not always require the complexity of a dual-differential subtractor because electrically adjacent gages share a common circuit node. The triferential subtractor is defined to simplify signal conditioning for adjacent gages. A triferential subtractor can be as simple as a classical inverter implemented with a single operational amplifier and two resistors. A variety of five- and three-wire signal conditioning circuits were illustrated. Some of these circuits can provide an Anderson loop "front end" for conventional strain gage bridge amplifiers.

References

1. Anderson, Karl F., Constant Current Loop Impedance Measuring System That Is Immune to the Effects of Parasitic Impedances, U.S. Patent No. 5,731,469, December 1994.
2. Anderson, Karl F., "The Constant Current Loop: A New Paradigm for Resistance Signal Conditioning" NASA TM-104260, October 1992.
3. Parker, Allen R., Jr., "Simultaneous Measurement of Temperature and Strain Using Four Connecting Wires, " NASA TM-104721, November 1993.
4. Anderson, Karl F., "Current Loop Signal Conditioning: Practical Applications, " NASA TM-4636, January 1995.
5. Anderson, Karl F., "A Conversion of Wheatstone Bridge to Current-Loop Signal Conditioning for Strain Gages, " NASA TM-104309, April 1995.
6. Anderson, Karl F., Continuous Measurement of Both Thermoelectric and Impedance Based Signals Using Either AC or DC Excitation, *Measurement Science Conference*, January 1997.
7. Hill, Gerald M., "High Accuracy Temperature Measurements Using RTDs With Current Loop Conditioning, " NASA TM-107416, May 1997..
8. Olney, Candida D. and Collura, Joseph V., "A Limited In-Flight Evaluation of the Constant Current Loop Strain Measurement Method, " NASA TM-104331, August 1997
9. Anderson, Karl F., "The Anderson Loop: Your Successor to the Wheatstone Bridge? ," IEEE Instrumentation and Measurement Magazine, Vol. 1, No. 1, March 1998.

References are available at http://www.vm-usa.com/links.html