Your Successor to the Wheatstone Bridge? NASA’s Anderson Loop

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March, 1998

I. INTRODUCTION

A new measurement circuit topology known as the Anderson loop is challenging the venerable Wheatstone bridge in a number of applications areas. Known primarily for making lead-wire problems become irrelevant and for its larger output, the “loop” also offers other significant advantages compared to the “bridge” (as the Anderson loop and Wheatstone bridge will usually be called for simplicity). The loop circuit was invented to deal with lead-wire resistance variation problems that occurred when connecting high-temperature strain gages to conventional bridge signal conditioning in the Flight Loads Laboratory of the NASA Dryden Flight Research Center. A simple blending of continuous analog subtraction with Kelvin sensing, NASA’s loop measurement circuit proved to be an enabling topology that benefits a wide variety of instrumentation and measurement applications. NASA obtained a patent for the concept which they make available for commercialization

Before getting to the details, it is important to keep separate some different loop topologies and their purposes. There is the current loop topology commonly found in process instrumentation, measurement and control applications and as well as a current loop approach for the comparison of standards. And you can find current loops used to assess the difference between standard impedances that are close to the same value. Basically, when a loop circuit depends on continuous analog dual-differential subtraction to accomplish its function, it is an “Anderson” loop.

The Wheatstone bridge has been a standard measurement circuit for over a century and for good reasons. Indicators such as galvanometers and earphones do not load the Wheatstone bridge measurement circuit at balance conditions. Some derivative of the Wheatstone bridge can reliably estimate almost any resistive and reactive electrical quantity when the product of the opposite bridge arm impedances is adjusted to be equal. These are powerful credits for a venerable circuit topology.

The advent of variable resistance strain gages provided the transducer designer with a linear sensing element of essentially infinite resolution. The Wheatstone bridge was called on to operate away from balance conditions when strain gages were designed into transducers. Excellent transducers based on off-balance bridge operation became widely available at reasonable prices. DC-coupled amplifiers with good stability arrived replacing higher-performance (but higher-cost) carrier-based designs to observe the output of bridge transducers in simple, effective signal conditioners.

II. BRIDGE CIRCUIT LIMITATIONS

As an electrical circuit for variable-impedance sensor element signal conditioning, the classic Wheatstone bridge provides a number of well-known advantages. They may be found presented in depth in any electrical measurement handbook. But features that provide advantages for one application can be disadvantages for another. Some bridge topology characteristics that might be regarded as limitations are:

- Half the signal from each element’s impedance change is attenuated by adjacent bridge arms.
- The output signal is usually a nonlinear function of impedance change per individual bridge arm.
- Multiple sensing impedances observed simultaneously provide only a single output signal that is typically a fixed function of the sensor element impedance changes.
- Each individual sensing impedance variation is typically able to influence only one measurement output.
- Lead-wire and connector impedance changes typically add measurement uncertainty, particularly when they occur in the inter-bridge wiring and especially when the various changes do not evolve identically.

- As many as nine lead-wires may be required per bridge transducer to impose a reliable excitation level and precisely alter the output of the transducer to accomplish an end-to-end system electrical calibration.
- The transfer function, including compensation, of a bridge transducer is essentially “locked in” — typically not adjustable after manufacture and very rarely adjustable after installation when the actual operating environment becomes known.
- Thermoelectric (self-generating) outputs are difficult to separate from continuous impedance change (non-self-generating) outputs when using DC excitation.

III. DUAL-DIFFERENTIAL SUBTRACTION

The 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 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.

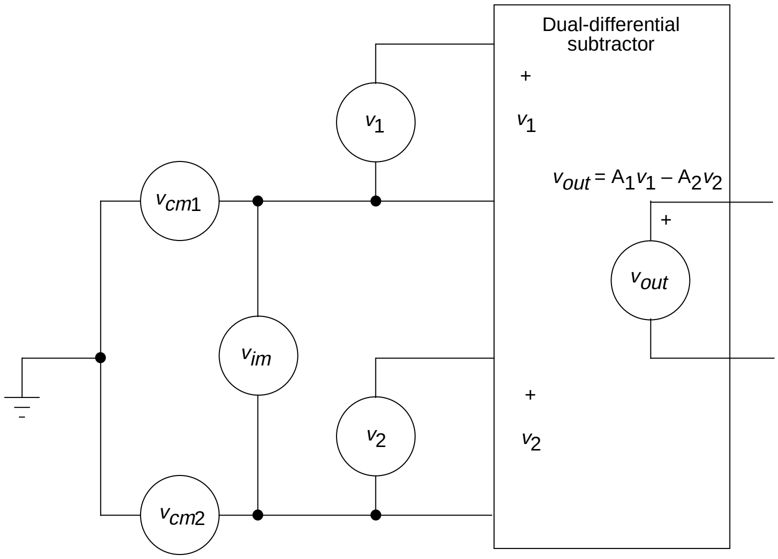

Figure 1, The dual-differential subtractor

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 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, $v_{cm\,1}$ and $v_{cm\,2}$, or interior mode potential difference from one input to the other, v_{im}.

IV. THE ANDERSON LOOP MEASUREMENT CIRCUIT TOPOLOGY

If a practical dual-differential subtractor with sufficiently high input impedance and rejection of unwanted signals in the loop measurement circuit topology (Fig. 2) is used, voltage drops along current-carrying lead-wires, Z_{w1} and Z_{w2} are simply not included in the signals being processed.

No significant voltage drop occurs along the sensing lead-wires, Z_{w3} and Z_{w4}. Therefore system models typically have no need for wire or connector impedance terms. Lead-wire resistance becomes essentially irrelevant in practical applications.

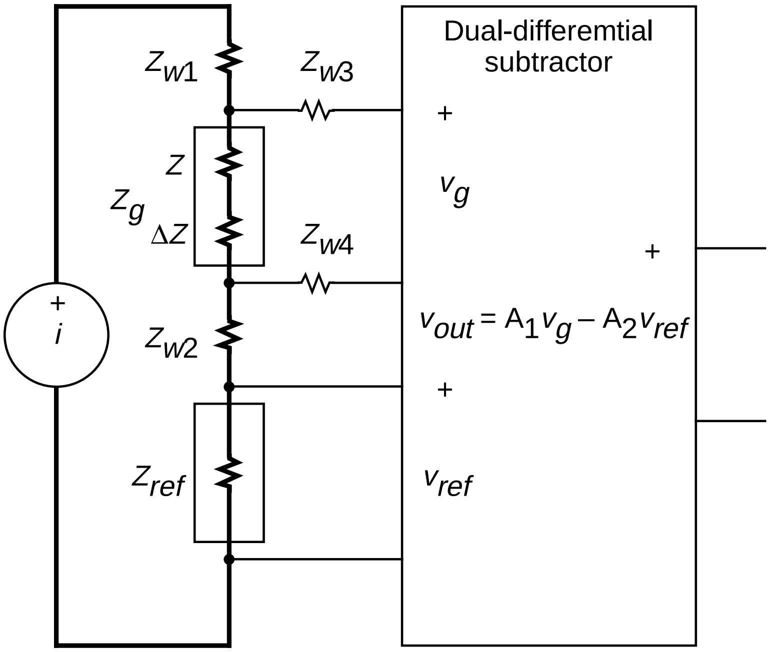

Figure 2, The Anderson loop measurement circuit topology

When the reference impedance, Z_{ref}, is chosen to be equal to the initial impedance, Z_g, of a sensing element, and the subtractor inputs are processed with unity gain then the output is

$$v_{out} = i\Delta Z \tag{1}$$

The result indicates that the loop has an inherently linear response to changes in a sensor element and no impedance terms are present to attenuate the output. Also, unlike typical Kelvin observations, any variation in the excitation level, i, appears in the output as a percent-of-reading error rather than as a percent-of-excitation error. The excitation may be any useful waveform and can be unregulated when performing ratiometric measurements. For simplicity, constant direct current is often used for excitation.

A. Ratiometric Operation

Ratiometric operation of the loop is achieved by normalizing v_{out} to v_{ref}. This is commonly accomplished by using the same voltage reference to regulate the voltage across Z_{ref} (and thereby regulate loop current) and as the reference input to the voltmeter A/D converter. Loop current regulation is theoretically unnecessary when v_{ref} is used as the reference input to the voltmeter A/D converter but the converter output becomes indeterminate should the loop inadvertently open in operation.

B. Multiple Loop Sensor Impedances

Other sensor impedances can exist in the loop because their voltage drops will not be relevant unless they are observed by the input of another subtractor. A subtractor can observe the voltage drops across two different (and not necessarily adjacent) impedances in the loop. The subtractor output represents the instantaneous difference in the impedances of the two sensor elements, much as a Wheatstone bridge responds to sensing element changes in its adjacent arms. The example presented later in Fig. 4 illustrates this approach.

C. Noise Rejection

Each voltage drop across a sensing impedance is observed differentially. This approach serves to reject noise from the environment according to the common mode rejection of the system. To maximize the common mode rejection achieved in a measurement system it is important to minimize the opportunities for common-to-normal mode voltage conversion caused by unequal impedances between the various sensing elements in the loop and their environments. As with bridge circuit conditioners, it is often desirable to use a floating excitation supply in loop circuit conditioners to maximize common mode rejection performance.

D. Subtractor Gain Adjustment

Sensors based on bridge circuits typically require each impedance in the bridge to be precisely trimmed to some desired value, whereas loop circuits can tolerate wide impedance variations among sensing elements they contain. Using the subtractor defined in Fig. 1 and adjusting gains A_1 and A_2 can force the voltage drop across any impedance to appear at the output port as though it had been observed across $A(Z + \Delta Z)$. Therefore any element impedance that is convenient to manufacture may be used without trimming in the transducer itself, as though the element had been manufactured and installed with uncommon precision.

E. Wheatstone Bridge Equivalence

Loop circuits can have double the output of a bridge for the same sensor impedance and power dissipation. The sensitivity of a loop circuit is defined in Eq. 1. The equivalent linear approximation for the change in output from the change in impedance of a single sensor element in a Wheatstone bridge circuits is

$$v_{out} = i\Delta Z / 2 \tag{2}$$

Because voltage divider circuits are not used in loop circuits to accomplish active subtraction there is not a “2” in the denominator of the equation relating output voltage to sensor current and sensor impedance change. This accounts for the loop delivering double the output voltage for the same power dissipation in its sensing elements when compared to the Wheatstone bridge.

F. Similar Topologies

Industrial process monitoring and control situations often involve noise pick-up from the environment and wire resistance problems. A ubiquitous solution to these problems involves using a “transmitter” device located close to an associated sensor. The transmitter is typically powered by a conveniently located voltage source which also powers several other transmitters. Each transmitter acts as a two-terminal series current regulator having the magnitude of its current controlled by the physical phenomenon being observed. The range of current in the loop extends from some maximum level down to 5% of that level, thereby assuring that an open in the loop resulting in zero current is not mistaken for a normal situation. 4 to 20 mA is the most commonly used current range in process control because it makes almost 4 mA of current available to power the electronics in the transmitter.

Standards labs frequently acquire measurements using a constant current flowing through each of two or more impedances connected in series. A differential voltmeter reads the voltage drop across each impedance, usually to determine the difference in impedance between a standard and other impedances. This approach requires that the range and resolution of the voltmeter be sufficient to observe small differences (on the order of microvolts) between large voltages (on the order of volts). Note that this technique involves a sequential numerical rather than a continuous analog subtraction.

While it is possible to implement a sampling dual-differential subtraction using this method, the approach tends to be significantly slower and often more expensive due to the high resolution and linearity required of the voltmeter. Errors will develop related to the time when samples are taken if sampling is not sufficiently simultaneous to deal with the dynamics of the situation being observed. Aliasing errors can also become troublesome. Continuous analog subtraction is likely to provide superior rejection of noise (especially excitation-related noise) common to both subtractor inputs.

V. A SIMPLE SUBTRACTOR

The overall quality of loop signal conditioning is primarily a function of the active subtractor’s quality. The presentation of the variety of designs for subtractors, data validity assurance features, sensor impedance identification, end-to-end electrical calibration and offset adjustment features now in operational use is beyond the scope of this paper. Those published to date may be found in the references.

The simplest dual-differential subtractors are built from appropriately connected instrumentation amplifier (IA) integrated circuit components. However, not all off-the-shelf IA components have the linearity, common mode rejection and temperature stability necessary for a unity-gain subtractor in applications such as strain gage signal conditioning. The designer must choose IA components having acceptably small input- and output-referenced errors.

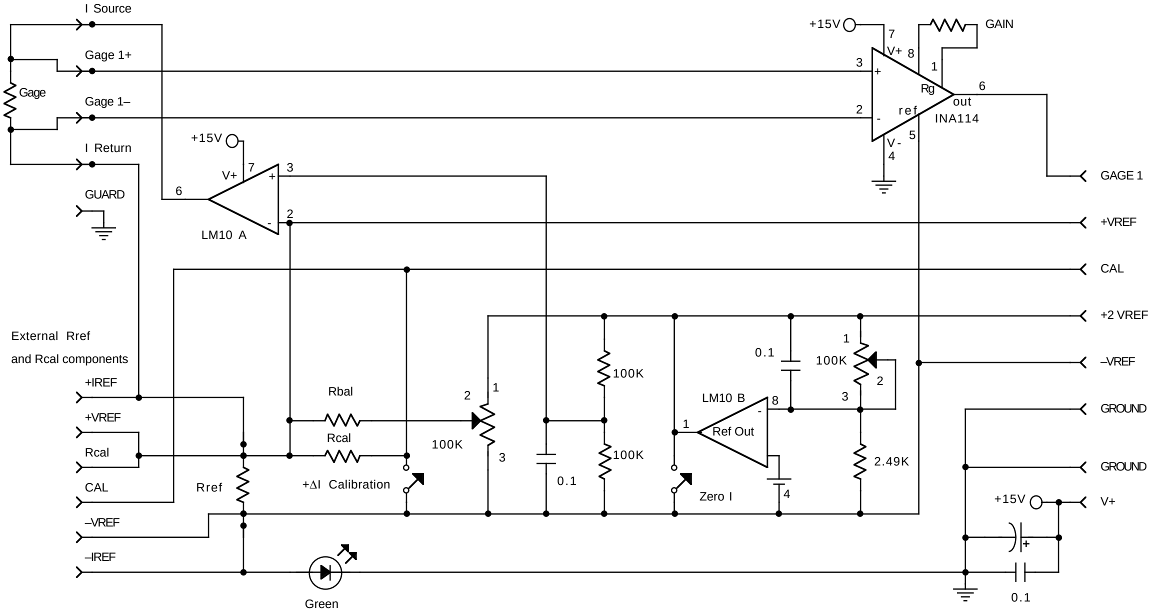

Figure 3, A single-sensor Anderson Loop signal conditioner

An IA component replicates at its output the potential difference observed at its input (with gain when desired). The output is delivered with respect to the potential to which its reference terminal is tied.

The single sensor loop signal conditioner schematic in Fig. 3 shows a single-component IA (INA114) acting to replicate the voltage sensed at its input where the result can be differentially observed in series opposition with the voltage across Rref. Amplification of the IA is set by the GAIN resistor (often omitted to provide unity gain operation). The two sections of the LM10 serve to establish an adjustable voltage level at pin 1 that is double the desired voltage across Rref, divide this voltage by two and filter it to serve as the set-point to the current regulator which delivers its output at LM10 pin 6 (I Source). Loop current through a sensor returns (at I Return) to flow through the

Kelvin-connected reference resistor, Rref. As demonstrated later in an experiment, wires connecting the sensor to the signal-conditioner circuit (Z1-4) have essentially no influence on the circuit's output. The voltage across Rref provides the feedback to the current regulator. Rbal either injects or draws a small current into the feedback node to vary the ratio of sensor current to the current through Rref, providing a simple offset control as its associated potentiometer is adjusted. Activating the +ΔI Calibration switch causes Rcal to make a predictable change in sensor current while the voltage across Rref is held constant. This action establishes an end-to-end electrical sensitivity calibration for the signal conditioner and associated voltmeter. The green LED provides a level about 2 volts above the negative rail to assure that the INA114 operates properly even when the loop current is caused to approach zero when the Zero I switch is activated to cause the current regulator set-point to become zero volts.

The excitation-off zero control is an imperative in the discipline of Measurement Engineering to assure that valid measurements are achieved. (The indication from a valid measurement leads the knowledgeable observer to an appropriate decision.) If you observe *any* signal when there is no excitation current, then you have a corresponding uncertainty in your measurements that should be regarded as a random error unless proven to be otherwise.

The I Source potential can also be used to drive a guard shield at an essentially constant voltage level with respect to the sensor. Any moderate leakage current supplied by this node does not change the current through the sensor.

VI. MULTI-SENSOR LOOPS

Several IA components can each act as one half of a dual-differential subtractor by observing sensor and reference voltage drops across several sensing elements in an loop. This is accomplished by tying all their reference terminals to the same potential. In this role, each IA is called a "half-subtractor" because it serves to replicate its input (with appropriate gain) where it can be observed in series opposition to the output of any other IA used for the same function.

The difference in the voltage drop across any pair of observed sensors (or sensor groups) is thereby made available as a differential output voltage observed from one IA output terminal to another IA output terminal. So any sensor impedance in an

Anderson loop can be used in any number of different outputs derived from a single transducer.

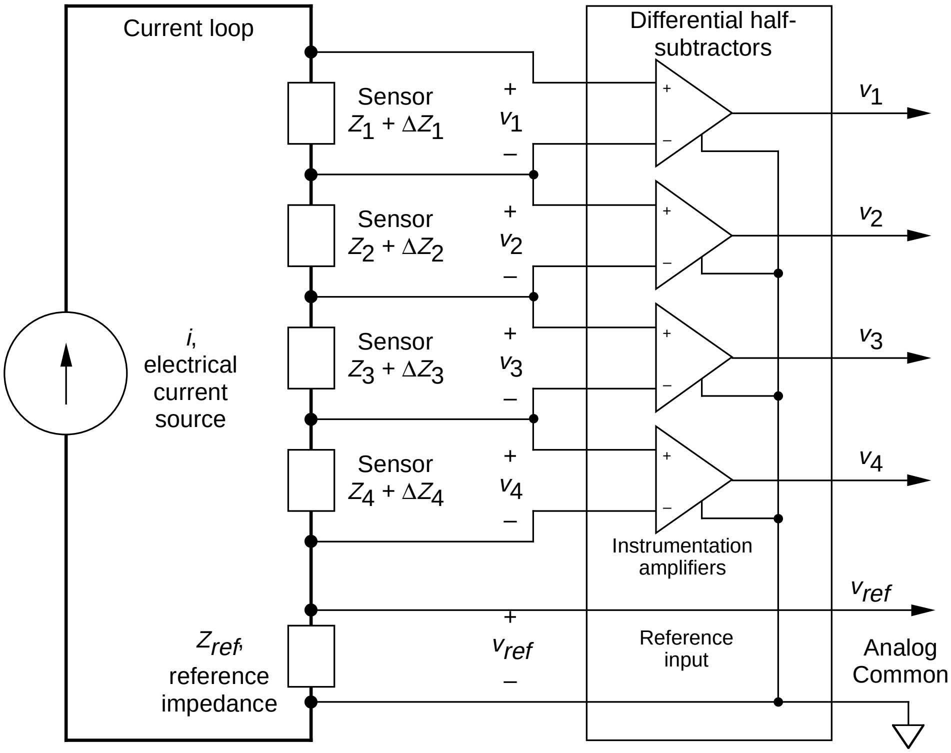

Figure 4, Instrumentation amplifiers used as Anderson loop half-subtractors

The pairs of sensor differences available directly from the individual elements previously arranged in a Wheatstone bridge are illustrated in Fig. 4. This wiring configuration shares sense lead-wires. If the more negative end of one sensor impedance, say Z_1, and the more positive end of an adjacent impedance, say Z_2, are both at essentially the same potential, then the same sense lead-wire can accomplish both observations. This configuration requires a total number of lead-wires equal to three plus the number of impedances in the loop.

A strain gage rosette consists of three adjacent strain gages and, by sharing sense lead-wire functions, requires only six wires to obtain immunity to random lead-wire impedance variations. The Anderson loop system seemingly achieves the impossible — two wires per observed impedance yet wire impedance variations do not cause uncertainty in observing the strain gage resistance variations.

When the initial impedance of each sensing element is the same as the reference impedance, the arrangement of sensing elements and subtractors in Fig. 4 yields the following outputs:

$$v_1 - v_{ref} = i\Delta Z_1 \tag{3}$$

$$v_2 - v_{ref} = i\Delta Z_2 \tag{4}$$

$$v_3 - v_{ref} = i\Delta Z_3 \tag{5}$$

$$v_4 - v_{ref} = i\Delta Z_4 \tag{6}$$

$$v_1 - v_2 = i(\Delta Z_1 - \Delta Z_2) \tag{7}$$

$$v_1 - v_3 = i(\Delta Z_1 - \Delta Z_3) \tag{8}$$

$$v_1 - v_4 = i(\Delta Z_1 - \Delta Z_4) \tag{9}$$

$$v_2 - v_3 = i(\Delta Z_2 - \Delta Z_3) \tag{10}$$

$$v_2 - v_4 = i(\Delta Z_2 - \Delta Z_4) \tag{11}$$

$$v_3 - v_4 = i(\Delta Z_3 - \Delta Z_4) \tag{12}$$

VII. ANDERSON LOOP BENEFITS

The Anderson loop measurement circuit topology can be implemented to remove the previously discussed limitations of the Wheatstone bridge topology by using “active” subtraction to observe the change in the output level of the variable impedance element(s) instead of the “passive” subtraction accomplished by the arrangement of the elements in a Wheatstone bridge circuit.

Some of the benefits that have been demonstrated using the loop circuit are:

- Larger and inherently linear outputs that are individually available from each element in a sensor.
- Sensor power dissipation is lowered in portable and temperature-sensitive applications.

- Even random lead-wire and connector variations are tolerated without a need for expensive transmitters nearby in hostile environments or the removal of systematic errors from the resulting data.
- Fewer, smaller and less expensive lead-wires are required in tight installations.
- Quieter engineering unit readouts are available.
- Smarter sensors can be designed to deliver multi-axis and multi-parameter outputs from simpler sensing structures.
- Stiffer sensors can have twice the frequency response for the same output level.
- Temperature compensation and calibration refinements can be implemented after installation by adjustments conveniently away from the sensor — within the signal conditioner.

VIII. A FOUR-SENSOR ANDERSON LOOP SIGNAL CONDITIONER

The concept illustrated in Fig. 4 is presented as a signal-conditioner design in Fig. 5. Practical features such as gain and offset controls per sensor and RFI protection are included, in addition to calibration and uncertainty identification capabilities.

The single-sensor loop signal conditioning circuit accomplishes its offset adjustment by varying the sensor current while the reference voltage is held constant. When several sensors are in the same loop, this approach is not useful because every sensor typically needs a different offset adjustment. An individual offset unique to each sensor is called for when several sensors occupy the same loop. The four-sensor schematic of Fig. 5 shows one convenient way of accomplishing individual offsets while preserving the ability to simultaneously implement all of the above equations.

A pair of voltages (+OFFSET REF and –OFFSET REF) are established just above and below the potential at the more negative end of R_{ref}. These reference levels establish voltage levels above and below –VREF with which to drive the various reference terminals of the half-subtractor IAs. The command causing the loop current to become zero also removes offsets from the half-subtractors. This approach ratiometrically offsets each half-subtractor IA with respect to the level of loop current while preserving the linearity of the system.

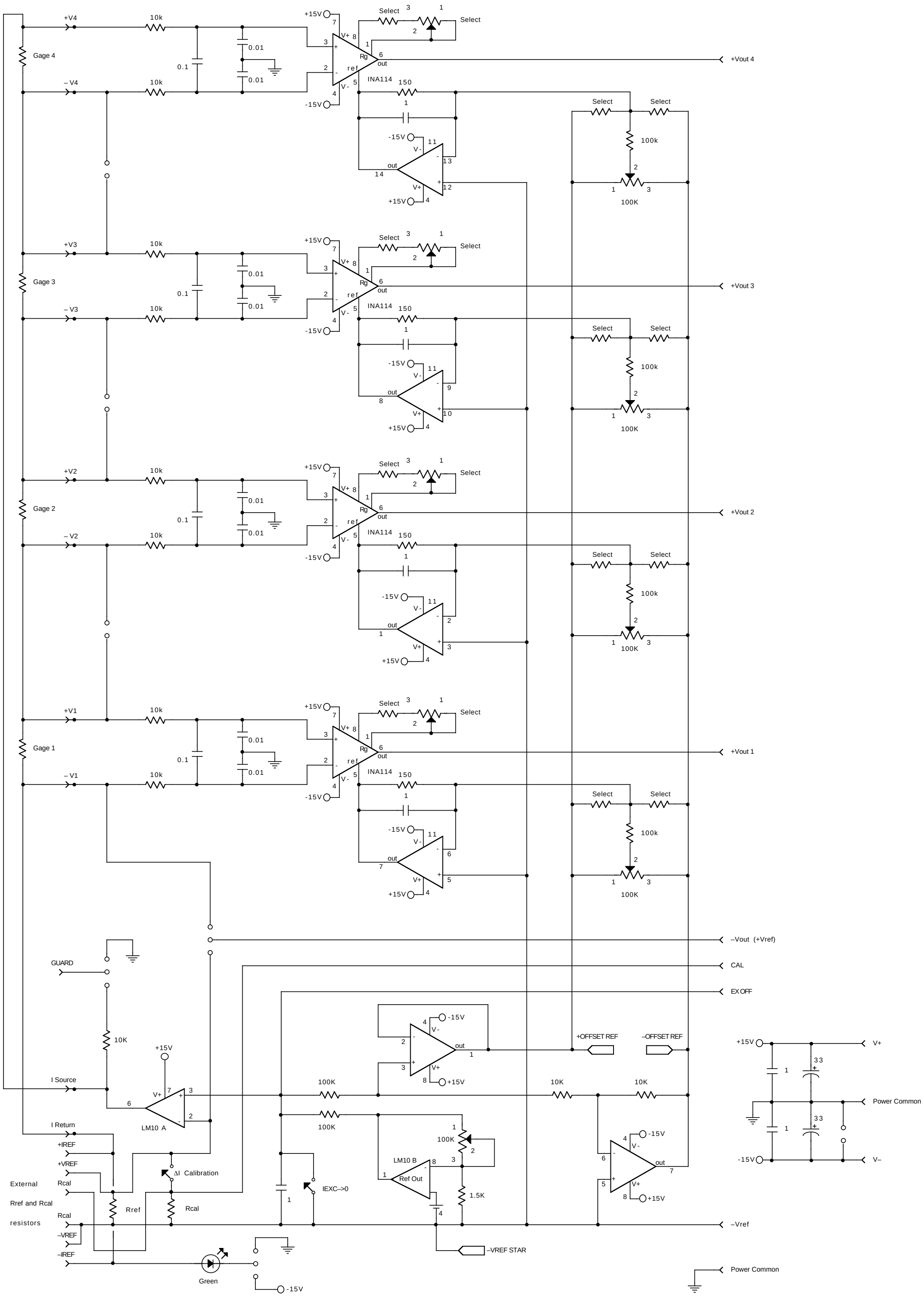

Fig. 5, A four-sensor Anderson loop signal conditioner

Each IA has an individual gain adjustment if required. And each IA input has an RFI-suppression filter at its input. If all sensors are being individually observed, then the same calibration approach is used as described for the single-sensor conditioner.

But, if the difference between sensors is being observed, then the usual approach is to shunt the sensor with a much larger resistance in order to achieve an end-to-end system electrical calibration.

IX. THE ANDERSON LOOP IN ACTION

Today most operational Anderson loop measurement channels can be found in NASA research applications, concentrated at the Dryden Flight Research Center, Edwards, CA and at the Lewis Research Center, Cleveland OH. Dryden originated the concept and, not surpassingly, has the largest concentration of loop equipment, using the circuit for both flight- and ground-based research measurements. A NASA/USAF F16 XL-2 used the Anderson loop in flight on a “shock fence” installed under its left wing. This fence has several adjacent strain gages installed, some wired in bridge and others wired in loop circuits. Test results show that essentially the same data result from each configuration over a wide flight temperature range as well as at supersonic flight conditions. The Boeing Company’s Damage Dosimeter is another airborne strain-sensing measurement application.

Two structural research test applications from Dryden involve test panels that were installed in the Dryden Flight Loads Laboratory. These buckling and shear panel tests successfully used over 400 Anderson loop measurement channels.

Another application involves a “rake” installation attached to the floor of a wind tunnel at the Lewis Research Center. The rake gathers data on the distribution of temperatures and pressures upstream from a model aircraft engine inlet. Loop circuits are used with resistance temperature detectors (RTDs) to obtain temperature measurements. The Anderson loop can obtain particularly good temperature difference measurements from RTDs located upstream and downstream from the model inlet when they are wired in the same current loop and observed with the same subtractor.

X. TRANSDUCER AND SYSTEM DESIGN POSSIBILITIES

The Anderson loop provides a set of tools for the measurement system designer that can accomplish previously unrealistic requirements. This section summarizes several proven transducer (and measurement system) design possibilities.

A. Wires and Connectors

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

B. Sensor Element Wiring Arrangements

A subtractor input port can observe an $i(Z + Z_w)$ signal. This approach can be used with existing three-wire installations of strain gages and resistance thermometers. All of the various advantages of the loop topology remain except, of course, that lead-wire impedances must change alike in order to avoid output uncertainties (as is required of conventional wire-impedance compensation circuits). This arrangement can allow a three-wire current loop sensor to perform as well as a four-wire bridge sensor.

C. Quantity of Sensor Elements

There is no need to have any particular number of sensors in a loop (as opposed to the four essentially identical sensor arm impedances found in most bridge-based sensors). So Anderson loop transducers can be designed with any number of sensor elements. Two sensing elements in a transducer may simplify designs that presently require four elements to implement the bridge configuration previously essential for accomplishing analog subtraction.

D. Multiple Use of Sensor Elements

The same sensing element can be used as a calculating or compensating element in any number of sensor outputs. This is accomplished by observing the same sensor output as an input to each of an arbitrary quantity of subtractors. This approach is illustrated in Fig. 4. Since amplification unique to each sensor is available in each dual-differential subtractor, the same sensing impedance can be observed by an arbitrary number of subtractors and appear to be any desired magnitude in each of many different outputs. This allows calibration and compensation to be adjusted after installation in the field by simple component ratio (potentiometer) adjustments in the signal conditioning of loop circuits. And the various impedances in a sensor can have conveniently different initial values.

The loop signal conditioning approach can, by adjusting gains A_1 and A_2 within the signal conditioner, vary apparent sensing element impedance in the field after transducer installation to deal with the actual (but imperfect) sensor-element impedances, initial conditions and service environment. This measurement system design approach can, in effect, rotate the compensated output plot of a transducer's response with respect to an environmental influence to be any desired value at each of two arbitrarily selected conditions.

E. The Distributed Sensor

The same excitation current can be routed through several dispersed sensing impedances and, with Kelvin sensing carrying their voltage drops to subtractors in the signal conditioner, a “distributed sensor” is achieved. Precision accumulation of the sums and differences in the impedance changes of sensors, regardless of their physical dispersion, provides an opportunity to obtain especially accurate temperature difference measurements using resistance thermometers in widely-separated locations. And, the desensitization and instability caused by long inter-bridge wiring can be eliminated from weighing system designs.

F. Reduced Excitation Current

When the four gage impedances typically arranged in a Wheatstone bridge are wired in series rather than in series-parallel, the load on the excitation supply becomes $4Z$ instead of Z. Since the loop has twice the sensitivity of the bridge, the same output signal level can be achieved with only one-fourth of the excitation current normally applied to a bridge.

G. DC Signal Separation

If one connects to a sensing impedance, such as a strain gage, with thermocouple wire then classical Wheatstone bridge signal conditioning will present the thermoelectric and impedance change signals together. With DC excitation, each of these signals tends to become noise for the other. Some form of varying excitation is typically used to identify the self-generating (thermoelectric) and non-self-generating (impedance change) components of the signal. The dual-differential subtractor circuit function can be employed such that impedance-based and thermoelectric signals do not experience cross-talk even with DC excitation. Without additional lead-wires, both resistance change and temperature can each be continuously observed. No significant uncertainty is caused in the resistance change output by the presence of thermoelectric potentials. And, the significant voltage drops arising from a DC excitation current flowing through thermocouple wire leads can be arranged to induce insignificant errors in the temperature indication.

XI. PROBLEMS BECOME OPPORTUNITIES

The loop topology requires active components to accomplish dual-differential subtraction. The disadvantages of this approach relate to the disadvantages of using active components rather than a circuit arrangement of passive components alone to accomplish the analog subtraction function. Mitigating features provided by the loop often cause the disadvantages to become an acceptable cost.

A. Measurement System Noise

The addition of an active element in the signal path of a measurement system can add noise to the system. This is, of course, true for the active subtractors in a loop application. However, at the signal conditioner’s input, the signal from a simple remote bridge sensor that does not include an internal amplifier or nearby transmitter is likely to include a significant level of noise coupled from the environment between the sensor and its signal conditioning. The loop topology inherently provides double the usual signal when compared to the equivalent Wheatstone bridge topology. Environmental noise tends to be much larger than subtractor noise. So, in practice, the electrical noise floor at the outputs of active subtractors has been found to be essentially the same as the noise floor at the output of an equivalent Wheatstone bridge. Since the output signal level from each sensor element is not attenuated by a factor of two in an Anderson loop, the signal-to-noise level in the system output for the same measured level improves by almost 6 dB — a major boon for measurements in a noisy environment.

B. Dynamic Response

Loop-system performance is a direct function of subtractor performance. The dynamic response of the subtractor and the opportunity for electrical energy storage in the wiring that connects a sensor to its related subtractor will vary the dynamic response of a loop measurement system. The same factors limit the response of bridge-based systems. The electrical energy storage in bridge transducer output wiring alters system response and any energy storage in the intra-bridge wiring which arranges for passive voltage subtraction alters the passive subtractor’s response.

C. Fault Tolerance

Loop system fault tolerance is limited by its series topology. An open in the wiring that carries loop current will remove excitation from all sensors in the loop and an open in any sense wire disconnects the associated sensor(s) from associated subtractor(s) in the signal conditioner. Imperfect insulation resistance and short circuits will also influence the system output. Similar factors limit the fault tolerance of bridge-based systems. A fault in the wiring to or within the bridge is very likely to render the measurement unusable. Unlike the bridge, the loop may continue to yield useful data from sensing impedances in the loop that still function despite other problems. This is possible because loop subtractors will continue to operate even though there are anomalies in the loop circuit itself. For example, the measurement system can be designed to automatically bypass loop current around “opens” in the loop and thereby develop useful information from the sensors in the loop that still carry excitation current and remain well attached. So the loop can enable the designer to achieve more robust measurement system operation than can be provided by the bridge.

D. System Cost

The key difference between bridge and loop signal conditioning is the inclusion of one or more dual-differential subtractor functions. Today’s parts cost in volume to implement simple subtractors is well under $1 (U.S.). Particularly good subtractors can be implemented today in single quantities for under $10 (U.S.). It would be possible for multiple sensors in a loop to be conditioned by functions combined on one multi-differential subtractor integrated circuit chip. The chip could also include voltage reference and excitation regulation functions. Power supply, amplification, filtering, packaging, etc., requirements for the overall signal conditioning function remain essentially the same for both bridge and loop signal conditioners. However, loop excitation power requirements may be substantially lower.

XII. AN EXPERIMENT

A signal conditioner built from the single-sensor circuit schematic of Fig. 3 can be used to gather data that demonstrates the performance of a simple subtractor in an elementary Anderson loop. The experiment is designed to highlight the sensitivity of the circuit output to ΔZ and its immunity to a large variation in the impedance of its most sensitive lead-wire, Z_{w2}. This lead-wire has the greatest undesired influence on the circuit output because it varies the common-mode voltage to be rejected by the IA. (If Z_{w2} changed in a comparable Wheatstone bridge circuit, an output would be developed that is indistinguishable from a gage impedance change, ΔZ.)

Variations in Z_{w1} are accommodated by the constant current excitation source. Variations in Z_{w3} and Z_{w4} are insignificant when compared to the nominal 10^{10} ohm input impedance of the IA circuit employed to sense v_g. The INA114 instrumentation amplifier was selected for this application because it has a particularly low output-referenced error. The INA114 is specified as having a minimum of 75 decibels of common-mode voltage rejection at the unity gain operating condition.

The expected variation ΔZ_{cm}, in the observations, due to the change in lead-wire impedance Z_{w2} is a result of the finite IMRR of the subtractor. In the single-sensor loop circuit, IMRR is equal to the CMRR of the IA. ΔZ_{cm} is derived from subtractor CMRR by

$$\mathrm{CMRR} = v_{out} / v_{cm} \tag{13}$$

but

$$v_{cm} = i(\Delta Z_w) \tag{14}$$

and

$$v_{out} = i(\Delta Z_{cm}) \tag{15}$$

so
$$\Delta Z_{cm} = \Delta Z_w \text{ CMRR} \tag{16}$$

This result indicates that the most observable wire impedance change in Fig. 3 is rejected by a factor equal to the common-mode voltage rejection ratio of the IA circuit employed to accomplish analog subtraction. Theory suggests that no more than 0.0178 ohms of output indication will be observed due to a wire impedance change in Z_{w2} of 100 ohms between Z_g and Z_{ref} in the single-sensor loop circuit.

The experiment design varies sensed impedance change, ΔZ, in decades (0.00, 0.01, 0.10, 1.00 and 10.00 ohms) and wire impedance, Z_{w2}, is changed by an amount large enough (ΔZ_w = 100 ohms) to cause an observable output due to the finite common mode rejection of the IA. Initial gage impedance is 350 ohms. The excitation level was adjusted to cause v_{ref} to be 1.000 volts so i was 2.857 mA . The output data presented are all with respect to the initial indications where ΔZ and Z_{w2} values are referenced as zero. Data were obtained with a low-level 16-bit sigma-delta analog-to-digital converter interfaced to a computer. System sensitivity was numerically calibrated at ΔZ = 10 ohms with Z_{w2} = 0 ohms.

XII. RESULTS AND DISCUSSION

The data in Table I show that the circuit output is a reliable function of ΔZ. Observations of ΔZ with essentially zero wire resistance were well within the combined accuracy of the decade resistance standard used to create the change input and the A/D converter providing the readout. The expected maximum variance due to lead-wire resistance not perfectly rejected by the IA was 0.0178 ohms. The observed maximum variance from ideal was 0.0033 ohms, indicating the actual CMRR of the IA in this application was about 90 dB, 15 greater than the minimum of 75 dB guaranteed by the manufacturer.

It is apparent from these results that benefits predicted by current loop theory can be realized in practice. Note that, unlike for a bridge circuit, the lead-wire impedance, Z_{w2}, is varied with minimal change in output observations. Such lead-wire variation in a bridge circuit would render its output indications completely useless. But with the current loop circuit presented here, *any* single lead-wire can be varied by more than 100 ohms with resulting output variations that are, for most practical purposes, irrelevant. These test results agree with operational experience gained during several hundred hours of measurements from over 300 current loop signal conditioning channels.

TABLE I

RESULTS FROM ANDERSON LOOP SIGNAL CONDITIONING

ΔZ Variation (Ohms)	ΔZ Observed $Z_{w2} = 0\Omega$ (Ohms)	ΔZ Observed $Z_{w2} = 100\Omega$ (Ohms)	ΔZ_{cm} Variance (Ohms)
0.000	0.000 0	0.000 4	0.000 4
0.010	0.010 1	0.010 9	0.000 8
0.100	0.100 7	0.104 0	0.003 3
1.000	1.000 7	1.001 7	0.001 0
10.000	10.000 1	10.001 2	0.001 1

These results were obtained with a single-component subtractor. Results with significantly better linearity and rejection of wire-resistance variations have been achieved with higher-performance subtractors. The discussion of these more complex designs and their respective performance is beyond the scope of this paper.

XIII. SUMMARY

The Anderson loop is a simply implemented measurement circuit topology that uses active subtraction instead of the passive subtraction accomplished by the classic Wheatstone bridge. Larger, inherently linear signals from sensing element impedance change are available with less excitation power and without the use of transmitters to achieve immunity to wire resistance variations. Transducers can be designed with any convenient quantity of sensor elements. Transducer intelligence can be implemented within the signal conditioner. The change in a single sensing element can be used in several simultaneous measurements. Sensor elements can appear to have any desired impedance level and influence on any of several outputs. The separation of resistance variation signals from thermoelectric signals can be accomplished even while using DC excitation. Experimental measurements confirm that practical capabilities can be achieved in a simple system.

XIV. ACKNOWLEDGMENT

The continuing contributions of the author’s colleague Allen R. Parker, Jr., who first translated the theory of the Anderson loop signal conditioning concept into practical circuitry and software, are gratefully acknowledged.

XV. TRY IT FOR YOURSELF

Seeing for yourself is believing. So why not try the Anderson loop circuit yourself? The schematic diagrams for the single-sensor and four-sensor loop signal conditioners will demonstrate the fundamentals with reasonable (but elementary) dual-differential subtractors. Educational institutions and government agencies may request demonstration printed circuit boards from the Technology Commercialization Office, NASA Dryden Flight Research Center, P.O. Box 273, Edwards, CA 93523.

XVI. TO DIG DEEPER

More information on the Anderson loop can be found in various publications. The references listed below provide a fairly comprehensive set of references on loop technology.

Anderson, Karl F., “The Constant Current Loop: A New Paradigm for Resistance Signal Conditioning,” NASA TM-104260, October 1992.

Parker, Allen R., Jr., “Simultaneous Measurement of Temperature and Strain Using Four Connecting Wires,” NASA TM-104721, November 1993.

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.

Anderson, Karl F., “Current Loop Signal Conditioning: Practical Applications,” NASA TM-4636, January 1995.

Anderson, Karl F., “A Conversion of Wheatstone Bridge to Current-Loop Signal Conditioning for Strain Gages,” NASA TM-104309, April 1995.

Hill, Gerald M., “High Accuracy Temperature Measurements Using RTDs With Current Loop Conditioning,” NASA TM-107416, May 1997.

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.

Anderson, Karl F., Continuous Measurement of Both Thermoelectric and Impedance Based Signals Using Either AC or DC Excitation, *Measurement Science Conference*, January 1997.

Anderson, Karl F., “The New Current Loop: An Instrumentation and Measurement Circuit Topology,” IEEE Transactions on Instrumentation and Measurement, October 1997.

Smith, Dave and Searle, Ian, Damage Dosimeter: A Portable Battery Powered Data Acquisition Computer, *Western Regional Strain Gage Committee Meeting,* February 1998.

Anderson, Karl F., “Your Successor to the Wheatstone Bridge? NASA’s Anderson Loop,” IEEE Instrumentation and Measurement Magazine, March 1998. (This paper is based on the I&M Magazine article.)

Most of these references can be obtained without charge as PDF files through the Internet at:

http://www.vm-usa.com/links.html

Karl F. Anderson received degrees in electrical engineering and business administration from Kansas State University, Manhattan, in 1963. He was responsible for flight instrumentation systems as well as all ground facilities engineering at the NASA Dryden Flight Research Center during his civil service career from 1964 to 1995. Inventor of the Anderson loop, NASA’s patented measurement circuit topology developed as an alternative to the Wheatstone bridge, Mr. Anderson is the author or editor of numerous NASA technical publications, conference papers, magazine articles, and user’s manuals involving Anderson loop circuits. After his retirement from NASA, Mr. Anderson founded Valid Measurements in Lancaster, Calif., to spread this new technology. He can be reached by e-mail at karl@vm-usa.com or at 805-722-8255.