Continuous Measurement of Thermoelectric and Impedance-Based Signals Using AC or DC Excitation

Karl F. Anderson
Valid Measurements
3761 W. Ave. J14
Lancaster, CA 93536
(805) 722-8255

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Abstract

A technique based on the Anderson loop measurement circuit topology is presented that continuously observes both impedance change and thermoelectric signals while using either AC or DC excitation of the impedance. AC excitation provides better separation of the signals while DC excitation observes only resistance change and results in wider bandwidth. All of the Anderson loop circuit topology benefits are maintained. The technique is illustrated with the simultaneous measurement of resistance variations and temperature by connecting to a strain gage with thermocouple wire.

Introduction

The hostile environment lead-wire error problem in strain gage measurements was solved at NASA's Dryden Flight Research Center in 1992(1) with the invention of what is now generally known as the Anderson loop, a measurement circuit topology that outperforms the Wheatstone bridge in many measurement applications. In essence, the Anderson loop uses "active" subtraction instead of the "passive" subtraction accomplished by Wheatstone bridge circuits. Analog circuits can accomplish a continuous subtraction with good stability and bandwidth when used with either alternating or direct current excitation(2).

Anderson loop circuits using alternating current excitation followed by a phase-sensitive demodulator can significantly improve measurement accuracy over equivalent DC excitation systems. However, frequency response is limited with AC excitation to less than about 20 percent of the excitation frequency. Also, with higher excitation frequencies, any lead-wire capacitance variations appear to be sensor variations in the system output. Movement of any lead-wires will increasingly contaminate the output signal as excitation frequency increases.

The NASA thermostrain gage was predicted in theory(1), reduced to practice(3) and patented by NASA(4, 5). A reversing, constant-level of excitation was used to accomplish the separation of

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current- and thermoelectrically-induced voltages. Now, equivalent separation of such voltages can be accomplished with unregulated AC or DC excitation in ratiometric signal conditioning designs.

This paper presents both AC and DC excitation approaches for simultaneously observing sensor change and temperature at the sensor. The AC excitation approach can provide higher precision and noise immunity than is typically obtained with DC excitation and can respond to impedance changes. The DC approach for observing resistance change achieves simplicity and higher frequency response but depends on lead-wire resistance variations being alike during test operations (which has always been necessary in Wheatstone bridge circuitry).

Background

Thermocouples develop an output voltage in response to a temperature gradient along the length of the thermocouple wire — a self-generating signal. Strain gages experience a change in electrical resistance in response to strain — a non-self-generating signal.

Determining temperature by using a thermocouple involves interpreting the self-generated thermoelectric output voltage with appropriate reference temperature compensation. The electrical impedance of the thermocouple wire does not contribute to measurement uncertainty unless the wire carries a significant current. A small current is often used to assist in observing that the thermocouple circuit remains continuous (has not developed an “open” circuit).

To observe a change in electrical impedance one must observe the change in the voltage drop across the impedance due to an “excitation” current flowing through the impedance. Variable resistance strain gage signal conditioning has historically involved either constant voltage or constant current excitation to a Wheatstone bridge circuit containing strain gages and “completion” resistances in the bridge circuit where gages are not available.

IR drops caused by excitation current flowing through lead wires tend to be a problem that is “compensated for” in Wheatstone bridge-based signal conditioning circuits. The compensation typically involves some combination of three-wire connection to remote single gages and half-bridge circuits, remote full bridge circuits, constant current excitation and remote sensing of excitation level.

A newer approach is NASA’s Anderson loop measurement circuit topology which uses “active” subtraction to observe the change in the output level of the gage(s) instead of the “passive” subtraction accomplished by the Wheatstone bridge circuit. Anderson loop signal conditioning circuits typically have no need for wire resistance terms in their circuit equations. By using active subtractors, voltage drops along wires are simply not included in the signals being processed(1).

The ideal subtractor, illustrated in fig. 1, delivers at its output, v_{out} the difference between two input potential differences, v_1 and v_2, and is uninfluenced by any common potential difference, v_{cm1} and v_{cm2}, or interior mode potential difference from one input to the other, v_{im}. Subtractors can be implemented with dual-differential amplifiers. The electronic circuit blocks which accomplish active subtraction in measurement circuits have come to be known as Anderson subtractors. A variety of subtractor designs are in operational use(2).

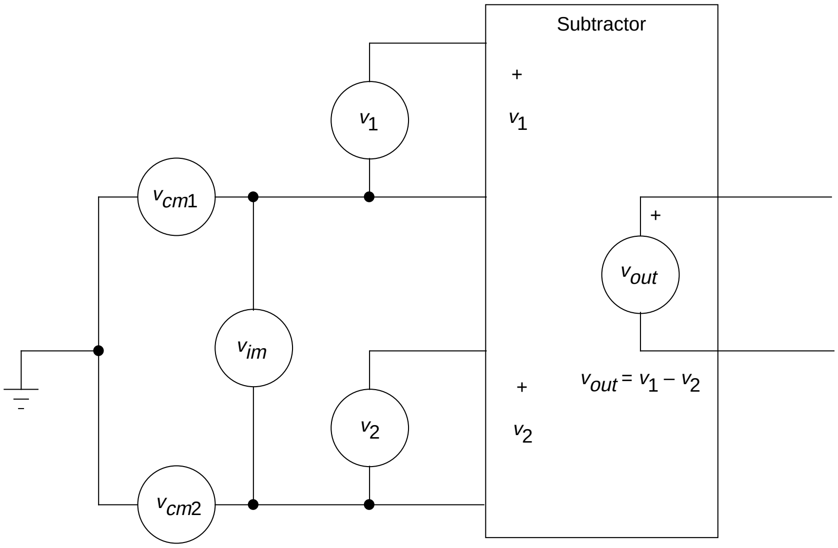

Figure 1, Ideal subtractor

DC Excitation

One observer's noise may be another observer's data. This is the case for self-generating thermoelectric voltages, often called "thermals." Thermoelectric voltages can contribute uncertainty to measurements, especially when using DC excitation to develop an output from non-self-generating sensors like strain gages. Yet thermocouples are a common device for measuring temperature. The design problem is to separate signals so each is essentially uninfluenced by the other.

Anderson subtractors can be used to compensate for IR drops due to DC currents flowing in thermocouple wires. This approach can produce a thermoelectric output that is largely uninfluenced by current flowing through wires to excite one or more strain gages.

A thermocouple wire pair is used both to connect excitation and to sense the voltage level at each terminal of a variable impedance sensor — a strain gage in the system illustrated in fig. 2. Any thermocouple type can be used. Using a Type T (copper/copper-nickel) thermocouple will minimize the lead-wire voltage drop to be rejected when the copper wire conducts the excitation current and the copper-nickel (constantan™) wire senses the voltage at the sensor. A reference temperature for the thermocouple is established in the conventional manner at an isothermal block.

DC Signal Separation

Referring to fig. 2, a DC excitation source supplies a constant current, I, to flow through a series circuit including one (or more) remote resistances, $R + \Delta R$, strain gages in this illustration. Thermocouple-wire pairs are used to connect each end of the gage (or gages in series) to the signal conditioner. The voltages observed at the inputs of the two Anderson subtractors are as follows:

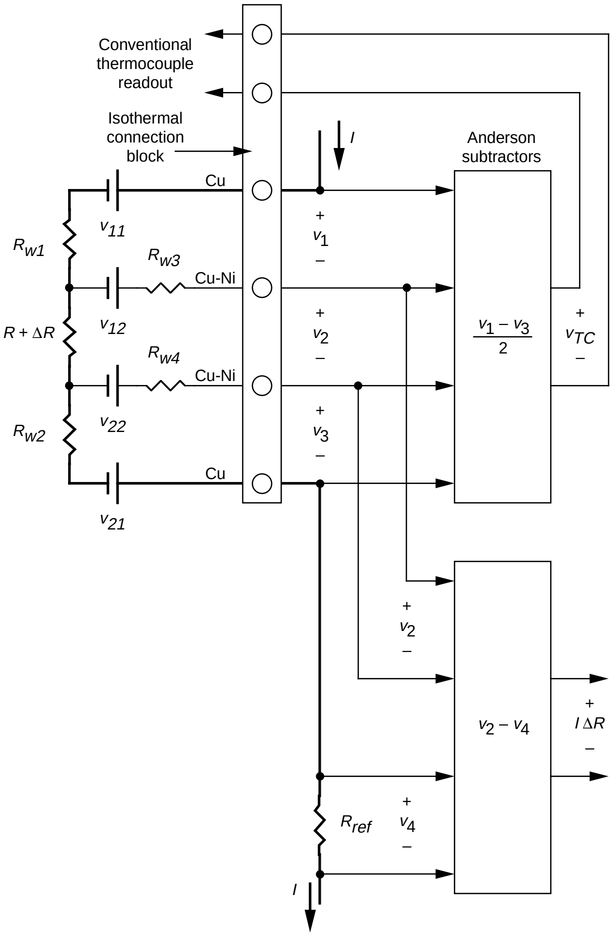

Figure 2, Thermostrain gage signal conditioning with DC excitation

$$v_1 = v_{11} + IR_{w1} - v_{12} \tag{1}$$

$$v_2 = v_{12} + I(R + \Delta R) - v_{22} \tag{2}$$

$$v_3 = -v_{21} + IRw_2 + v_{22} \tag{3}$$

$$v_4 = IR_{ref} \tag{4}$$

The thermocouple wires will have essentially the same electrical resistance when they are the same wire size, length, and alloy — a reasonable assumption when they are cut from the same spool of thermocouple wire in the process of obtaining lead-wires for the strain gage installation. Therefore R_{w1} may be analyzed as essentially equal to R_{w2} and R_{w3} as essentially equal to R_{w4}.

Additionally, $v_{11} - v_{12}$ and $v_{21} - v_{22}$ are defined as the net thermoelectric component, v_{TC1} and v_{TC2}, respectively, from thermocouple wires due to temperature gradients along their length. The average of these two thermoelectric voltages, analyzed with respect to the temperature of the isothermal block (the "reference temperature"), represents the temperature where the wires are connected to the remote strain gage.

R_{ref} is selected to be essentially equal to the initial resistance of the strain gage, R. This component serves a function similar to a "bridge completion resistor" in classical Wheatstone bridge signal conditioning.

When the Anderson subtractors have a sufficiently high input impedance, then there is essentially no "IR" voltage drop along R_{w3} and R_{w4}.

By making substitutions in the equations as indicated above, along with using Anderson subtractors as indicated in fig. 2 to process these four voltages, the resulting outputs become:

$$v_1 - v_3 = 2\, v_{TC} \tag{5}$$

$$v_2 - v_4 = I\Delta R \tag{6}$$

Temperature Readout

Eq. 5 derives the desired thermoelectric output essentially uninfluenced by excitation current flowing through the thermocouple wires. Here we depend on wire resistance changes being essentially alike in both R_{w1} and R_{w2}. This is equivalent to the classical "three-wire" technique for subtraction of lead resistance effects in Wheatstone bridge circuits that observe remote one- and two-strain gage outputs.

One-half the level calculated by eq. 5 represents the average temperature at the thermocouple wire connection point at the strain gage. If half this level is presented for readout by using more of the same type thermocouple wire connected to the isothermal block at the thermocouple subtractor output, then a conventional thermocouple indicator will reliably indicate the temperature at the strain gage.

Resistance differences in thermocouple lead wires found in practice require a "wire balance" adjustment in the signal conditioner. This adjustment will minimize any apparent temperature error due to lead wire differences that develop during system operation. Also, a subtractor offset adjustment may be useful to minimize bias in temperature indications. The implementation of these adjustments is discussed in a later section.

Strain Readout

Eq. 6 derives the desired strain gage resistance change output as a function of excitation current. This output is essentially uninfluenced by either thermoelectric voltages or random variations in wire resistance.

If v_4 were taken across an adjacent strain gage, R_2, (not illustrated) then the output would be equal to the excitation current, I, multiplied by ΔR_1 minus ΔR_2. This is equivalent to the classic Wheatstone "half-bridge" arrangement of strain gages.

These strain signals may be processed by the same amplifier designs used to condition the output of the Wheatstone bridge measurement circuit topology, including automated features for dealing with excitation, balance, amplification, offset, shunt calibration, etc.

Potential Error Sources

Should the thermocouple wires used to sense the strain output differ somewhat in their self-generating output, that difference will appear as a drift in the strain indication. Also, the removal of wire resistance effects depends on any initial difference in wire resistance ($R_{W1} - Rw_2$) remaining constant. This ideal situation can be difficult to achieve in practice.

The Anderson subtractors which develop the thermoelectric output must (1) have no appreciable voltage offset and (2) account for any initial difference in wire resistance which would cause the wire resistance IR drops being subtracted to differ from each other. Without appropriate circuits to set the system initial conditions, each of these offsets will appear in the output as a systematic temperature error.

Voltage offsets in the Anderson subtractors are removed by deriving an offset adjustment from a fixed voltage reference. Wire unbalance offsets are removed by deriving a separate offset adjustment from the loop current level. This approach retains the effectiveness of the offset adjustments should the loop excitation current level vary slightly.

Confidence Checks

The DC excitation technique depends on the current-carrying thermocouple wire resistances changing by *the same magnitude of resistance* in the environment. If their change in resistance differs in magnitude after the initial wire balance adjustment, then a drift in the derived temperature output will result.

Fortunately, the observer can determine whether or not wire resistance variations have become a problem — simply reduce the excitation current to zero and see if a significant change in indicated temperature occurs. Also, when the excitation current is zero there should be no output from the strain gage. The signal conditioner output with zero excitation, and with the thermocouple wire pairs each shorted within the signal conditioner may be used in lieu of analog offset adjustments. This approach becomes practical when excitation current is held constant and the offset signal levels can appropriately removed after analog-to-digital conversion by appropriate signal processing.

Should noise remain with excitation current removed, self-generating noise is entering the measurement system, typically coupled magnetically or capacitively from the environment. Should the strain indication become noisy when excitation current is turned on, either the excitation supply is noisy or impedance variations are occurring that appear as if the strain gage has been changing. Anderson loop measurement circuit topology tends to make unwanted impedance variation effects irrelevant in strain indications so long as the change is not within the sensed gage resistance(s). However, wire and connector impedance variations could cause the wire resistance difference ($R_{W1} - Rw_2$) to vary and thereby develop uncertainty in the thermocouple output.

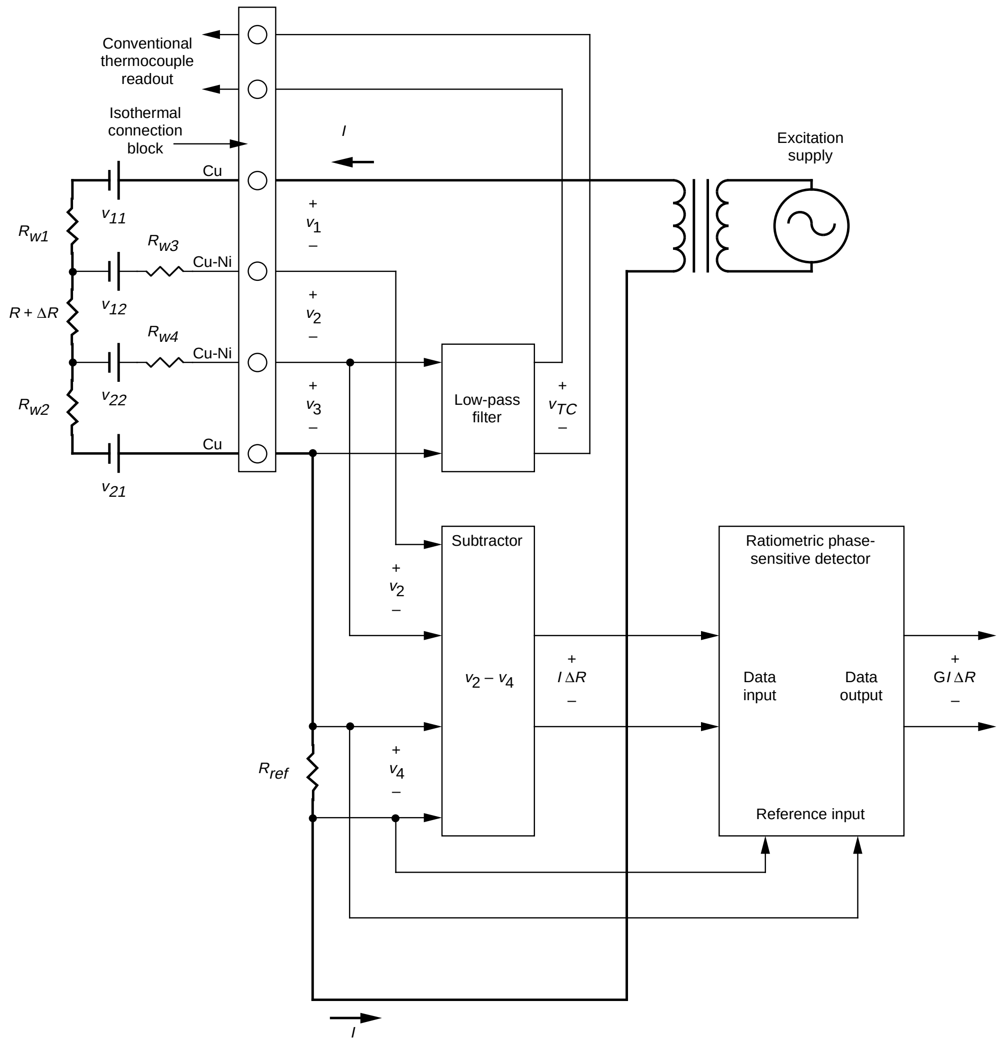

Figure 3, Thermostrain gage signal conditioning with AC excitation

AC Excitation

Note that while the DC excitation configuration (fig. 2) requires two thermocouple pairs, the AC excitation configuration (fig. 3) requires only one thermocouple pair. The thermocouple pair is connected to the gage node electrically closest to the reference resistance to minimize common mode voltage seen by the low-pass filter. Any thermocouple type can be used as long as the impedance-observing electronics can deal with the amplified thermoelectric levels. Using a Type T (copper/copper-nickel) thermocouple will minimize the thermoelectric level to be rejected when the copper wire senses the voltage at the sensor and the constantan wire conducts the excitation current. The other terminal of the sensor is connected in a conventional manner, typically using a copper wire pair to complete a Kelvin connection.

Signal Separation

The separation of self-generating and non-self generating signals is traditionally accomplished by conditioning the signals with some form of alternating current (AC) excitation. AC excitation is used mainly to accomplish the rejection of noise that can exist within the bandwidth of the signal of interest. Thermals and power frequency interference can be completely rejected when alternating excitation is applied to an impedance and an output is developed through phase-sensitive demodulation. This is accomplished by using AC excitation to signals from the non-self-generating elements. These signals are translated to a portion of the frequency spectrum around the excitation frequency chosen to be well away from the self-generating signals. The details of AC signal conditioning design and operation are well known and beyond the scope of this paper.

With alternating excitation, any self-generating signal component, such as a thermoelectric voltage, can be observed independent of a non-self-generating signal resulting from the excitation flowing through the impedance being observed. This can be accomplished by simply low-pass filtering a signal containing the desired thermoelectric voltage and any IR drop caused by the excitation current flowing through the thermocouple wire impedance.

Potential Error Sources

It is essential to assure that the excitation to the sensor has no DC component. This is a critical matter in the system because any DC component in the excitation will result in an uncertainty in the observed thermoelectric output. When there is no DC component in the excitation, then the DC component of any signal observed from within the loop circuit must come from either a self-generating effect such as a thermoelectric voltage, or from the presence of a non-linear circuit element in the loop. Fortunately, thermocouple connections behave as linear circuit elements for practical purposes and transformer coupling of the excitation eliminates any residual DC level it may contain.

The output signal level developed by an excitation current flowing through an impedance is directly proportional to the applied excitation level. Therefore, the regulation of the excitation level has a direct influence on the accuracy of the measurement results. Excitation regulation is less important when the observing electronics operate ratiometrically to account for the actual excitation level when processing the measurement signals. The experience reported here was obtained using ratiometric phase sensitive demodulation to minimize the need for regulating the AC excitation level.

The impedance-based signal is processed through a ratiometric phase-sensitive demodulator which is insensitive to both excitation level drift and self-generating signals at its input. The thermoelectric level is processed through a conventional low-pass filter.

Experience

Both AC and DC excitation have been used to simultaneously measure strain and temperature using the techniques presented. Both approaches functioned well within their predicted limitations.

DC Excitation Results

A system employing DC excitation as illustrated in fig. 2 was constructed and tested. Type K (Chromel-Alumel) thermocouple wire was used for connection to a strain indicator calibrator decade resistance with 0.01 ohm adjustment resolution. The bandwidth of the strain indication system extended beyond 8 kHz and was primarily limited by the bandwidth of the subtractor and data amplifier used with the system.

As with AC excitation, strain and temperature related signals had no observable effect on each other. However, when 15 ft. of 30 gage Type K solid thermocouple wire was used for connection to an actual strain gage installation heated in an oven, the thermocouple wire resistance variations with temperature were not exactly alike and caused an observable error.

Temperature indication error due to imperfect matching of wire resistance changes in a DC excitation system will vary in practice with the actual wire, wire length and temperature gradients involved in a test operation. Longer and smaller wire and a greater temperature gradient each serve to increase the likelihood of temperature measurement error. The errors experienced in a test that varied from room temperature up to 750 °F over a period of about 30 minutes were a maximum of 15 °F. This was a systematic error that could be removed by observing the temperature output with the excitation level set temporarily to zero.

AC Excitation Results

A system employing AC excitation as illustrated in fig. 3 was constructed and tested. Type K thermocouple wire was used along with the same strain indicator calibrator and thermocouple indicator described earlier. When the AC excitation source was directly connected to excite the Anderson loop the strain output was unaffected by thermoelectric signals at the input but the thermoelectric output had a significant offset. The offset resulted from a small DC component in the AC excitation source. The AC excitation source was then transformer-coupled to the current loop to eliminate the possibility of a DC component in the excitation and the offset in the thermoelectric output was no longer present.

Step level changes in the observed resistance were obtained by cyclically paralleling it with another resistor through a high-speed multiplexer switch. The strain indication waveform showed the bandwidth limitation imposed by the excitation frequency since each half-cycle is essentially one sample in a sampled data system. The resistance changes had no observable effect on the thermoelectric output. The temperature indication with and without the AC excitation flowing through the thermocouple wire agreed within 0.1 °F (less than 3 microvolts of thermoelectric output), the resolution of the thermocouple indicator. Step changes in thermoelectric input provided by a thermocouple indicator calibrator had no observable effect on the strain gage output.

Conclusions

A technique based on the Anderson loop measurement circuit topology was demonstrated to continuously observe both impedance change and thermoelectric signals with either AC or DC excitation. AC excitation provided better separation of the signals while DC excitation results in wider bandwidth. All of the Anderson loop circuit topology benefits were maintained.

Simultaneous measurement of strain and temperature at the strain gage was successfully demonstrated by connecting a strain gage with thermocouple wire to Anderson loop signal conditioners using AC and DC excitation.

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