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# High Accuracy Temperature Measurements Using RTD's With Current Loop Conditioning

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## APPROACH

### Voltage difference scheme

An innovative current loop signal conditioning method, developed by Karl Anderson, an Instrumentation Systems Engineer at NASA's Dryden Flight Research Center, was originally developed to overcome the inherent difficulties associated with the classical Wheatstone bridge circuit for strain gage conditioning.<sup>3</sup> This design conveniently subtracts the bias voltage from the temperature measurement, allowing for a higher resolution in the measurement. This method was able to satisfy research requirements for a 0.1 °F measurement accuracy in the NASA Lewis Research Center's 9 x 15 Low Speed Wind Tunnel (9x15 LSWT). Figure 2 illustrates the theory behind the voltage difference measurement scheme.

The RTD is modeled as a combination of the initial resistance  $R_{GAGE}$  and the resistance change due to temperature,  $\Delta R$ . Wire resistance  $R_{w1} - R_{w4}$  is the resistance due to the lead wires. The instrumentation amplifier which senses the voltage across the sensor has a high enough input impedance that the current flow through these leads is negligible, and there is no voltage drop across  $R_{w3}$  or  $R_{w4}$ .  $R_{REF}$  is in series with the sensor with the same current flowing through both resistors. This develops a voltage  $V_{REF}$  which is equal to  $V_{GAGE}$  when  $R_{REF}$  equals  $R_{GAGE}$ , and is subtracted from the sensor voltage.

$$V_{OUT} = V_{RTD} - V_{REF}$$

$$V_{OUT} = (I_{EXCIT})(R_{GAGE} + \Delta R) - (I_{EXCIT})(R_{REF})$$

if  $R_{REF} = R_{GAGE}$  then

$$V_{OUT} = (I_{EXCIT})(\Delta R)$$

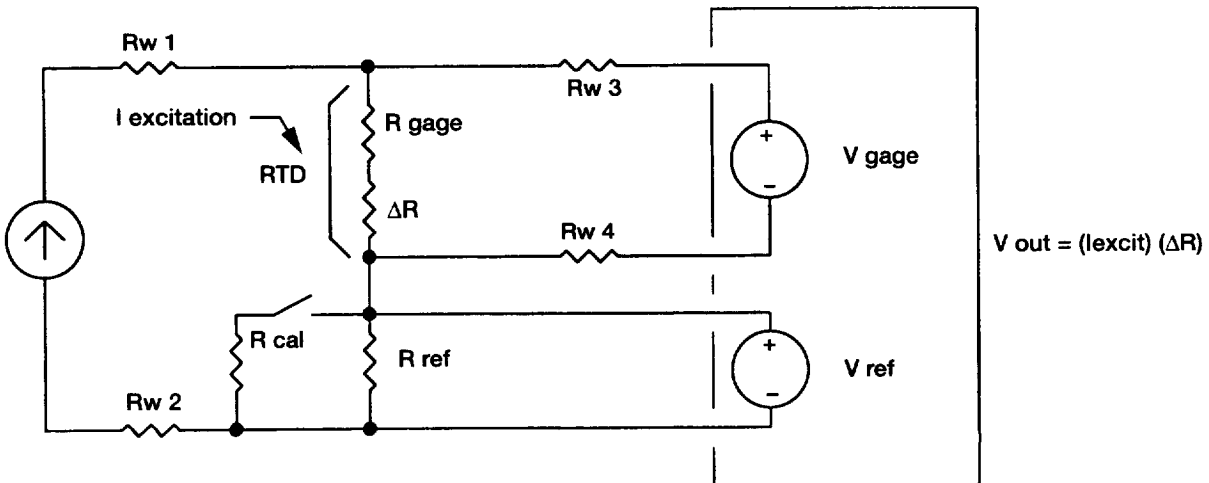


Figure 2.—Voltage difference measurement scheme.

The initial slight difference between the sensor resistance and the reference resistor is treated as an offset which is removed in the data reduction system. This results in an output voltage which is directly proportional to the difference between  $R_{REF}$  and  $R_{GAGE}$ .

**Circuit description**

The circuit used for a voltage difference measurement is shown in Figure 3. U1 is a LM10CLN type dual operational amplifier with voltage reference, configured in a constant current source circuit. By utilizing precision resistors with low temperature coefficients (<25 PPM), current drift due to temperature effects are minimized. The output of the first stage is  $2 V_{REF}$ , and is set by the ratio of R1 and R2. R3 and R4 divide this output by two, and is fed into the second stage of the op amp, which maintains the voltage across  $R_{REF}$  equal to  $V_{REF}$ . This output is the constant current  $I_{EXCIT}$ . The current loop is shown on Fig. 3 in bold. This current has been tested to have a drift of less than 0.02 % of excitation level, (100+ hour test in calibration facility, at constant temperature).

The current level can be monitored by observing  $V_{REF}$ .  $V_{GAGE}$  is sensed via the instrumentation amplifier (BURR BROWN INA114) which is used due to it high input impedance and low output referenced errors. This amplifier has a programmable gain which is set with a resistor,  $R_{GAIN}$ , across pins 1 and 8. For this test the gain equaled 10. The reference resistor is chosen to be equal to the gain times the nominal gage resistance,

$$R_{REF} = (Gain)(R_{GAGE})$$

$$R_{REF} = (10)(100 \Omega)$$

$$R_{REF} = 1000 \Omega$$

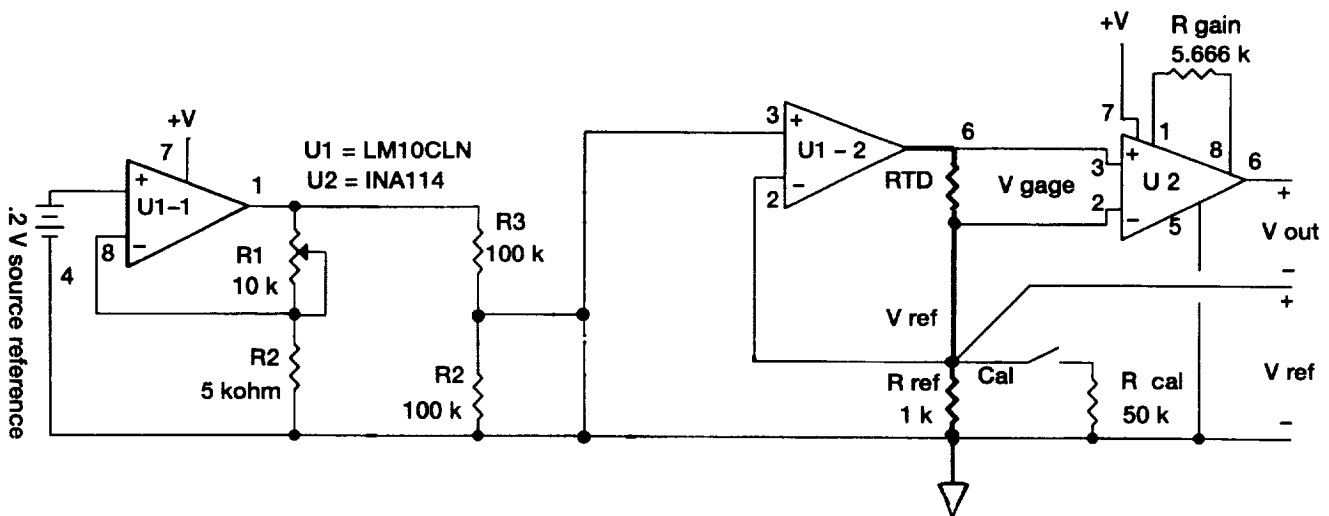


Figure 3.—Anderson loop circuit.

This ensures that the bias is subtracted from the temperature information. The RTD is connected in a 4 wire Kelvin connection.

The subtraction of the bias is done by connecting the amplifier's sense terminals (pins 2 and 3) across the sensor, the output reference terminal (pin 5) to the lower potential end of the reference resistor  $R_{REF}$  and taking the measurement output referenced to the positive side of  $R_{REF}$ . The resultant signal  $V_{OUT}$  is

$$V_{OUT} = V_{GAGE} - V_{REF}$$

which is the desired output. This is a floating differential output, with good S/N ratio and noise immunity.

This design minimizes the effect of excitation current variations. Since the current flows through both  $R_{GAGE}$  and  $R_{REF}$ , any change in  $I_{EXCIT}$  will result in a percent of reading error as opposed to a percent of full scale error.

### **Calibration Methodology**

The Anderson current loop provides for a convenient approach to calibrate the gage's overall system end-to-end sensitivity.<sup>4</sup> This is accomplished by changing the gage excitation current by a known amount,  $\Delta I_{CAL}$ . By shunting resistor  $R_{CAL}$  across  $R_{REF}$  with a switch, the additional current  $\Delta I_{CAL}$  flows through  $R_{GAGE}$ , and is calculated as

$$\Delta I_{CAL} = V_{REF}/R_{CAL}$$

The constant current regulator forces enough current through the loop to maintain the voltage drop across  $R_{REF}$  to equal the previously set reference level. The addition of  $\Delta I_{CAL}$  through the gage appears at the output as an increase in voltage,

$$\Delta V_{CAL} = \Delta I_{CAL} R_{GAGE} = I R_{CAL}$$

as if there is an increase in  $R_{GAGE}$ . This resistance can be sized to provide an apparent  $\Delta T$  which can be observed at the data system. This provides a reliable system measurement sensitivity factor when the  $R_{CAL}$  switch is closed.

## **UHB FAN TEST**

One aspect of a joint NASA and Pratt & Whitney UHB (Ultra High Bypass) Fan Program, which ran from February to September 1995 in the Lewis Research Center's 9 x 15 Low Speed Wind Tunnel, was to measure the fan's efficiency by the temperature change across the rotor. Four rakes with ten thermocouples located radially on each rake, were placed downstream of the rotor, evenly spaced circumferentially. They utilized measured extension leads, which were calibrated to minimize errors in

measurement. An additional rake consisting of ten 100  $\Omega$  platinum RTD's, (PRTD  $\alpha = 0.003923$ ) was included. Upstream of the model's bellmouth a reference freestream rake with one thermocouple placed at centerline, and four additional TCs at a 1 foot radius spaced at 0°, 90°, 180°, 270°, was installed to measure upstream temperatures. RTD's were also placed at a close proximity to the outer radius thermocouples. Extensive calibrations of the thermocouples yielded a 0.5 °F accuracy.

The RTD's were conditioned with the Anderson constant current loop method previously described. The excitation level,  $I_{EXCIT}$ , was chosen to be 0.5 mA to lessen the chance of self heating of the gage. With a temperature range of 32 to 150 °F the measurement would vary from 0 to 128 mV which was sampled with the facility's data acquisition system with a sensitivity of 0.042 °F/bit. The rakes were initially placed in a temperature stable oven and any offsets were normalized with a reference standard RTD probe (with 0.002 °F accuracy). The model was operated with the bellmouth and a variable fan exit nozzle (VFEN) at Mach 0.04.

## RESULTS

After allowing the temperature transients to settle, a scrolling plot was obtained for both the TC's and the RTD's on the reference freestream rake. The results of one data sequence are displayed in Fig. 4, where RTTTOA (RTD's), and RTTROA (TC's) were calculated as

$$RTRROA_{(1-4)} = REF \ RTD_{(1-4)} / REF \ RTD_A$$

$$RTTROA_{(1-5)} = REF \ TC_{(1-5)} / REF \ TC_{AVG}$$

where  $REF \ RTD_{AVG}$  and  $REF \ TC_{AVG}$  was the average of the four RTD's or five thermocouples respectively. While the calculated average temperature between the two methods of temperature measurement are within 0.13 °F (75.11 °F versus 74.98 °F), the spread of the thermocouples was greater than 0.74 °F, and the RTD spread was less than 0.08 °F over the same time period.

While there is still work to be done in optimizing the design of the RTD sensors used in an aero test environment, such as the large flow recoveries associated with the RTD sensor as opposed to thermocouples, calculations derived from the RTD measurements were comparable to those obtained with the calibrated thermocouples.

## LESSONS LEARNED

### Single Current Loop

Due to the time restraints imposed by the test, and the unfamiliarity with the possibilities that the Anderson loop provides, there are significant improvements possible which could further improve the validity of the measurement. For the P & W Fan test, all RTD's were conditioned with individual excitation

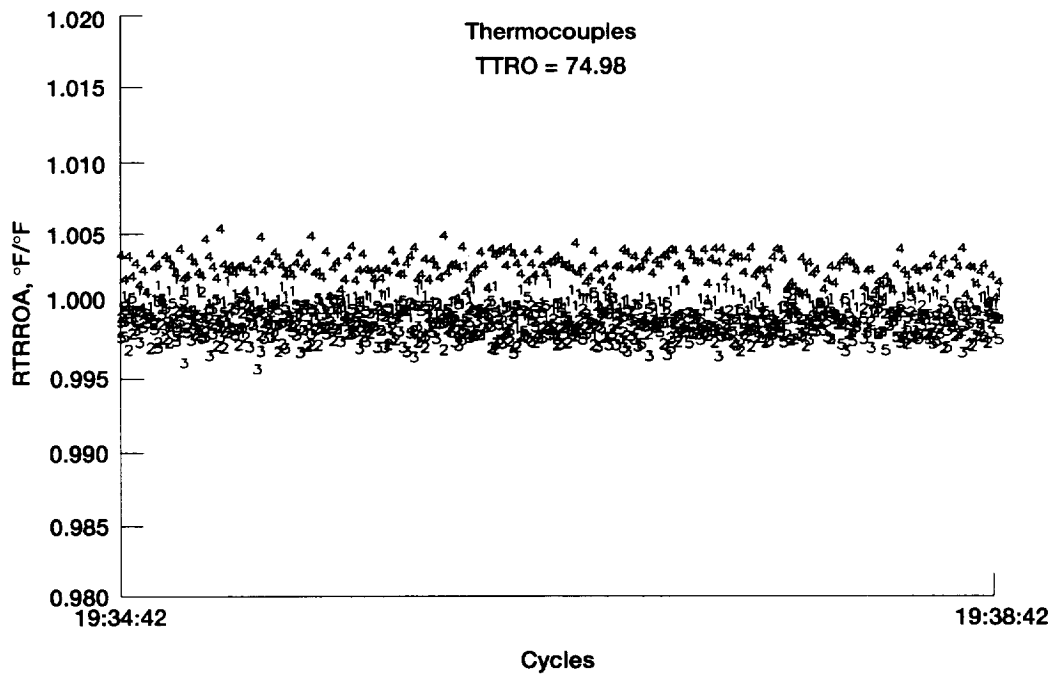
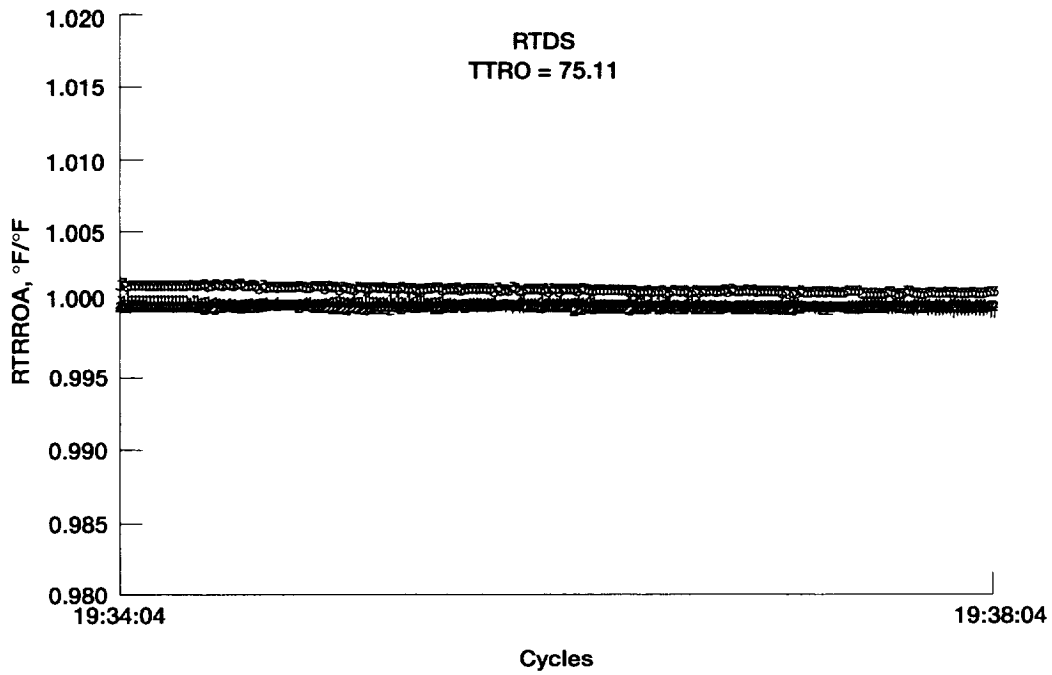


Figure 4.—Test data.

currents, from separate discrete conditioners. While the stability of the current source was proven at Lewis's calibration facility to be sufficient for the measurement, any variations between  $I_{EXCIT}$  levels would represent an error in measurement. By wiring all of the RTD's in both rakes into a single loop, one excitation current flows through all gages. Any variations would be the same in all gages, and it's associated error therefore minimized. An added benefit of this arrangement is the reduction in overall wires from 56 to 20. Figure 5 shows this configuration. To alleviate the possibility of having a broken wire or open gage break the loop and stop current flow in all gages, a silicon diode could be paralleled across each RTD to shunt the current in case of a failure. By keeping  $I_{EXCIT}$  low enough, the voltage drop across a working gage is far less than the level necessary to turn on the diode. In the event of a failure, the diode conducts so that the current continues to flow through the other gages. The outputs would be sensed individually by the facility data acquisition system, where the average temperature would be calculated and the difference in temperature determined.

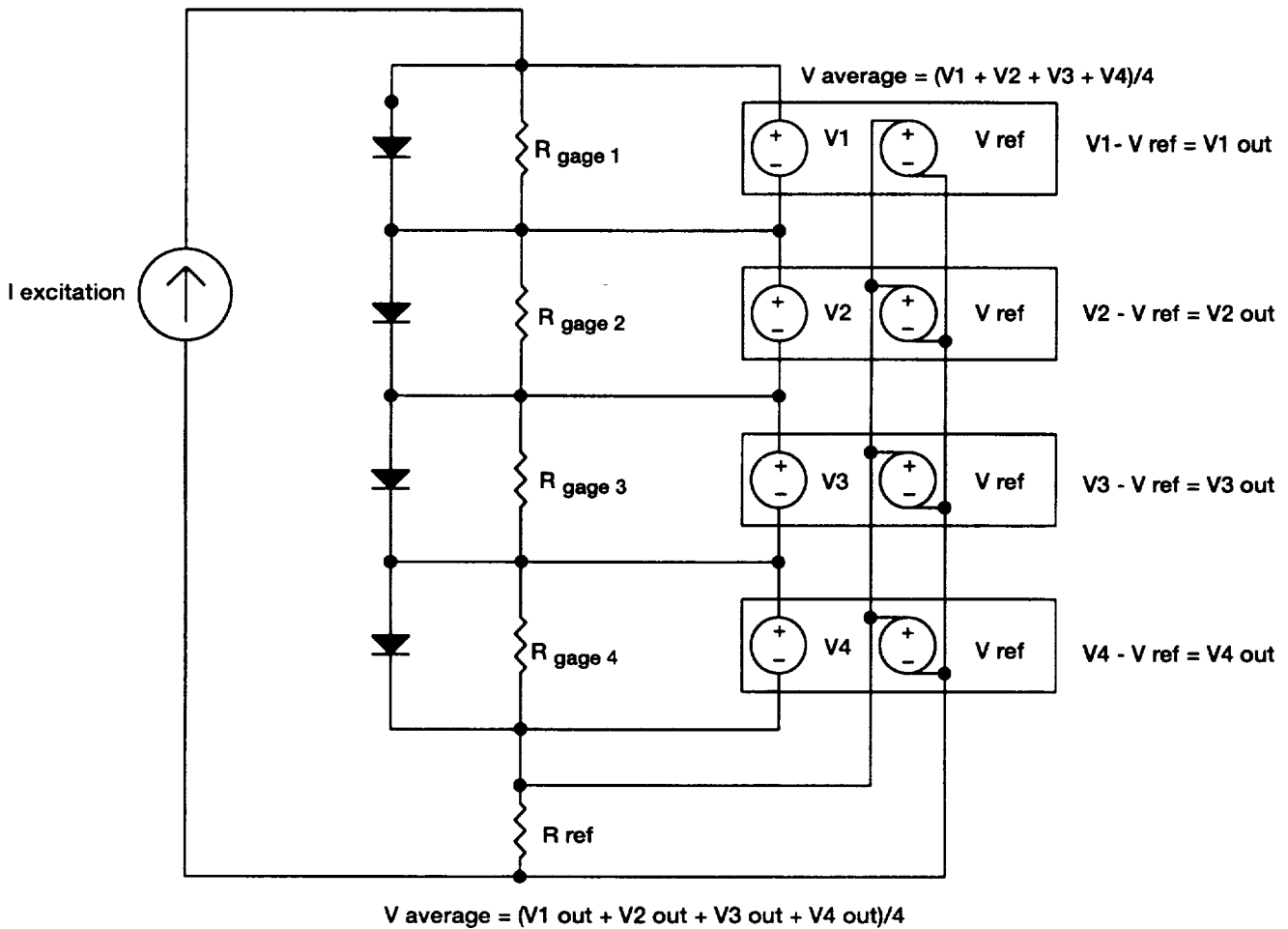


Figure 5.—Single loop arrangement for cruciform rake.



## Analog Computation

Another possible arrangement is to have the measurement averaging done before the data is input to the acquisition system. Output signals from both the duct and cruciform rake could be added through a summing amplifier arrangement, divided to find their respective averages, then viewed in series opposition to determine the difference in temperature measurement. This result would then be the input to the data system, thereby reducing the errors due to digitizing each gage's signal and the associated post calculations necessary for a temperature difference measurement.

## Multiple Loops With Same Reference Source

Alternatively, two regulators could be driven from the same  $V_{REF}$  source. This would provide for two current loops, one for each rake, that are referenced to the same level. This modification yields reduced errors as in the single loop configuration, but simplifies the analog averaging of each respective rake.

## Circuit Modifications

The circuit of Fig. 3 could be modified further to take advantage of the Anderson loop. These improvements are shown in the highlighted boxes of Fig. 6. To reduce any induced noise to the current regulator, a capacitor should be added from the positive input of the regulator, (pin 3 of the LM10CLN), to ground.

By adding a potentiometer, P1, connected to the  $2V_{REF}$  node, and connecting a series resistance,  $R_{OFFSET}$ , to the positive  $V_{REF}$  node, an offset adjustment derived from the excitation current level is possible.  $V_{OFFSET}$  is the difference between  $V_{REF}$  and the level and polarity set by the offset pot, (between 0 and  $2V_{REF}$ ). The offset current is limited by the series resistor so that

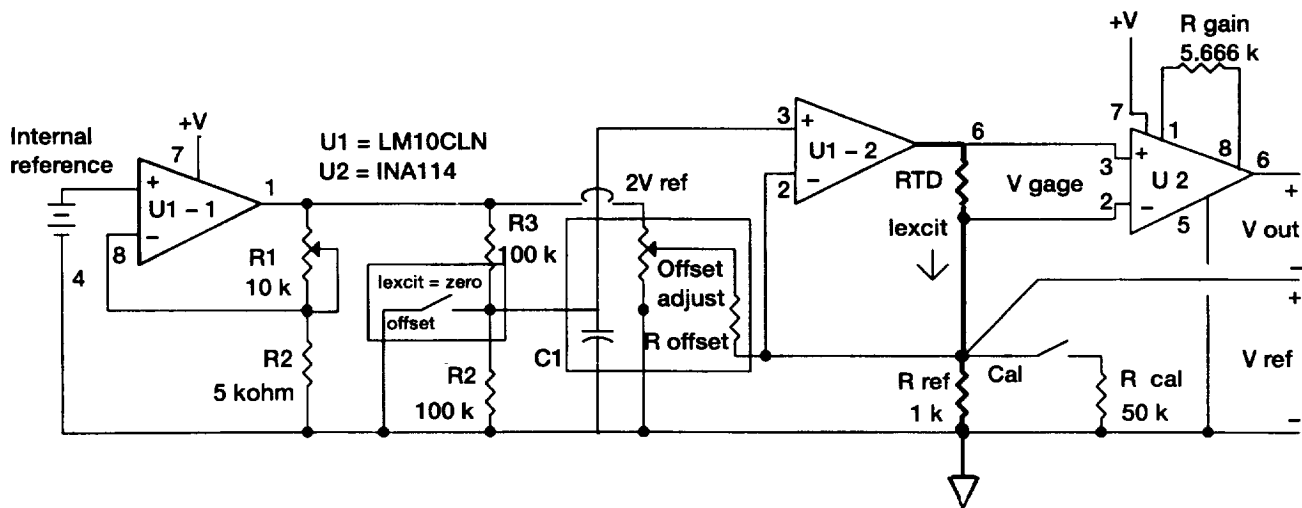


Figure 6.—Modified Anderson loop circuit.

$$\pm I_{\text{OFFSET}} = \pm V_{\text{OFFSET}} / R_{\text{OFFSET}}$$

This offset current is summed with the gage current,  $I_{\text{EXCITATION}}$ , to force the gage voltage,  $V_{\text{RTD}}$  to approach  $V_{\text{REF}}$ , which is the voltage drop across the reference resistor.

$$V_{\text{RTD}} = (I_{\text{REF}} + I_{\text{OFFSET}})R_{\text{RTD}}$$

A switch which shorts out R4 if added to the circuit would cause the excitation current,  $I_{\text{excitation}}$ , to become zero, providing a means of observing if self generating noise was entering the circuit. Since the circuit should only react to an impedance change, any output with the switch closed would be from noise, which adds uncertainty to the measurement.

## CONCLUSIONS

By utilizing the Anderson loop to condition RTD's in a wind tunnel environment, it was possible to achieve temperature measurements of a higher degree of accuracy than that obtained by thermocouples. The voltage difference method of dealing with the RTD's inherent voltage bias results in a higher sensitivity in the measurement. Resulting test data confirms that the use of the Anderson current loop to condition the RTD is an appropriate choice for accurate temperature measurements. The simplicity of the circuitry allows for easy setup, calibration, and verification of the sensor's signal.

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