AUTOMATIC LINEARITY CALIBRATION IN A RESISTANCE THERMOMETRY BRIDGE

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The paper describes a new system that automatically calibrates the linearity of a resistance thermometry bridge or readout. A thermometry bridge, like all measuring and test equipment, must be regularly tested to ensure it is operating properly and accurately. Previously, this could only be done using special equipment and time-consuming procedures. The new technique described in the paper facilitates more frequent calibration of a resistance thermometry bridge. The system is incorporated into the design of the bridge and thus requires no extra equipment. Calibration, once initiated, is performed automatically by the bridge and is relatively fast.

Tests were performed to evaluate the effectiveness of the automatic linearity calibration method. The uncertainty analysis and test results presented in the paper indicate that the technique is capable of quantifying resistance ratio measurement error as small as 2×10^{-8} and is effective at identifying a wide variety of failures when they occur.

Introduction

Equipment failures can and do happen. If a resistance thermometry bridge fails, the situation may go unnoticed but still cause measurement errors that produce incorrect calibrations of thermometers. It is important that a resistance thermometry bridge be regularly tested to ensure it is operating properly and accurately.

Perhaps the most thorough method of testing a resistance thermometry bridge uses a Resistance Bridge Calibrator (RBC) [1]. The device contains a set of precision resistors that can be switched in various series and parallel configurations. A calibration procedure using the RBC produces up to 70 resistance ratio measurements that, when analyzed, give an estimate of the measurement error at each test point.

While it may be considered the most thorough method and, in the author's opinion, should be an integral part of the periodic maintenance of a resistance thermometry bridge, the RBC method has some drawbacks that discourage regular and frequent use in a temperature calibration laboratory. The process requires special equipment—the RBC device. It is time consuming and may require several hours to complete the many measurements. During that time, the temperature of the RBC device must be held constant within a fraction of a degree Celsius. Also, the calibration is a manual process, requiring constant attention from the operator to set the switches of the RBC between each measurement. Finally, it requires the operator to perform the data analysis and interpret the results.

An ideal method of calibrating a resistance thermometry bridge would satisfy the following criteria:

1. The test equipment should be incorporated into the resistance thermometry bridge, so that no special equipment is necessary.

2. The test should operate automatically without user attention other than to start the test and observe the results. The necessary switching is electronically controlled.
3. Test resistors should be temperature controlled, so that the results will not be appreciably affected by temperature changes of the environment.
4. The test must adequately exercise the resistance thermometry bridge and be able to recognize practically any possible mode of failure.
5. It would also be beneficial if the system could complete the calibration relatively quickly. The less downtime, the better.

An automatic linearity calibration method, called Ratio Self-Calibration, has recently been developed that meets these requirements for a certain type of resistance thermometry bridge—a digital thermometry bridge that measures the ratio of two resistances using analog-to-digital converters [2, 3]. (The method is not suitable for current comparator bridges, and the author is also unable to suggest its use with AC resistance bridges.)

The Ratio Self-Calibration system uses resistance voltage dividers that are integrated into the digital thermometry bridge [4]. The system is entirely electronically controlled and allows quick, automatic linearity calibration that can be performed routinely without external equipment. Details of the Ratio Self-Calibration system are explained in the next sections. Following that, results of calibrations performed on several digital thermometry bridge are presented.

The Ratio Self-Calibration system

To better understand the Ratio Self-Calibration system, it is helpful to first be familiar with the basic principles of the digital thermometry bridge.

Operation of the digital thermometry bridge

A simplified diagram of the digital thermometry bridge is shown in Figure 1.

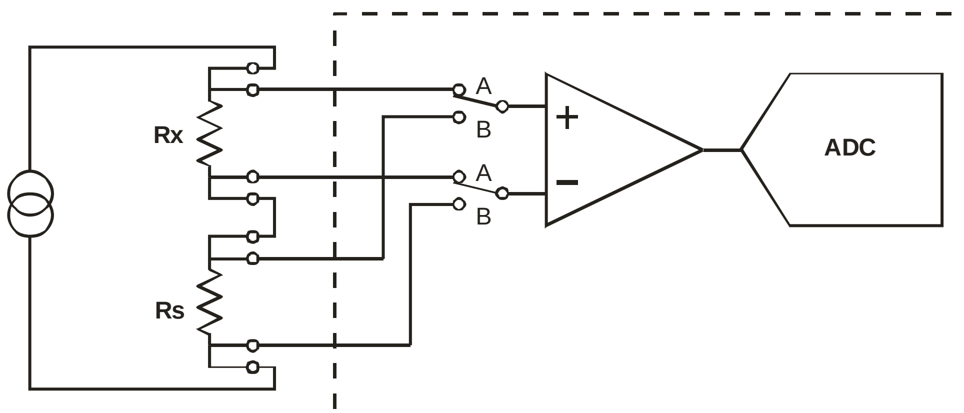

Figure 1. Diagram of the digital thermometry bridge

The two resistors being compared, R_X and R_S, are connected in series. A current source drives the same current through both resistors, producing a voltage potential on each that is proportional to its resistance. The analog-to-digital converter (ADC) samples the voltage from each resistor through electronically controlled switches. When the switches are in the A position, the ADC samples the R_X resistor. Then the switch is changed to the B position and the ADC samples the R_S resistor. An amplifier conditions and amplifies the voltages to minimize the effect of electrical noise. A processor (not shown) mathematically divides the two voltage readings to produce a measurement of the ratio of the two resistances. To cancel spurious EMFs, the operation is performed twice, the second time with the current in the reverse direction.

Nonlinearity can originate from several sources, including the ADC, amplifier, switches, and stray conductance in the electronic circuits. In most cases, the magnitude of measurement error will be smallest at resistance ratios near 0 and 1 and most significant at resistance ratios near 0.5. The measured resistance ratio, M_r, contains error, $e(r)$, that is a function of resistance ratio, r, as described by Equation 1.

$$M_r \;\approx\; r + e(r)\, r(r-1) \tag{1}$$

Ratio sum tests

Consider a test that replaces R_X and R_S with a simple resistance voltage divider comprised of two resistors, R_1 and R_2, as shown in Figure 2. In the first step of the test, the R_X input of the measurement circuit connects across R_1, the R_S input connects across both resistors, and the resulting resistance ratio (r_a) is measured (M_a). In the second step, the R_X connections are changed so that the resistance ratio (r_b) of R_2 over the sum ($R_1 + R_2$) is measured (M_b). When the two measurements are added, the result is expected to be 1.

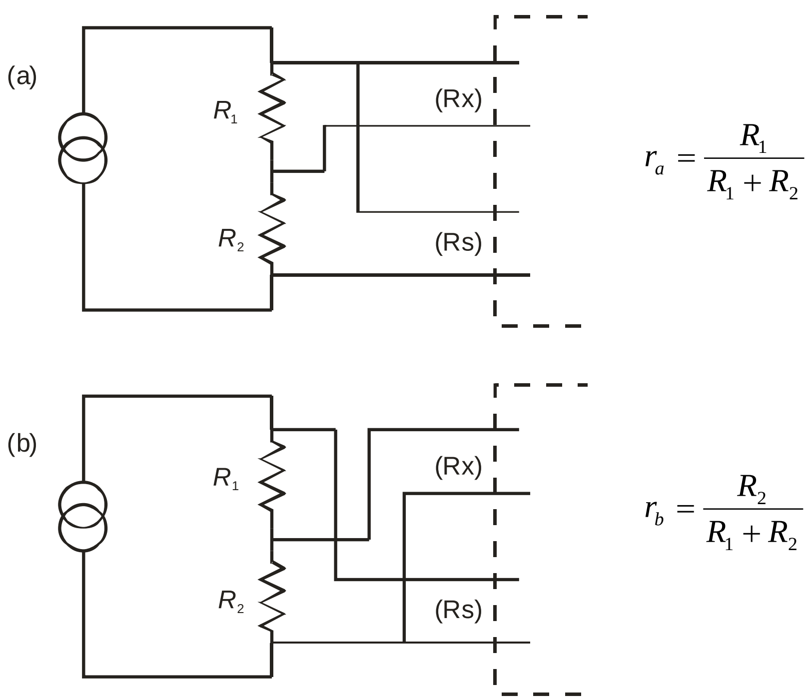

Figure 2. Measurement of a voltage divider

Consider the case where the two resistances R_1 and R_2 are approximately the same ($r_a \approx r_b \approx 0.5$). When the two measurements are added, the result is 1 plus some measurement error as shown in Equation (2).

$$M_a + M_b \approx 1 + \frac{1}{2}\, e\left(\frac{1}{2}\right) \qquad (R_1 \approx R_2) \tag{2}$$

This test, called "equal ratio sum," produces a direct determination of the measurement error at a resistance ratio of 0.5.

When measurement error is caused by nonlinearity of the ADC or amplifier, it is likely that the error will depend on the gain of the amplifier and the magnitude of the signal fed to the ADC. To more thoroughly exercise the digital thermometry bridge, the equal ratio sum test can be repeated with different levels of amplifier gain. As implemented in the author's system, Ratio Self-Calibration performs tests at five different levels of gain.

It may also be informative to perform a test with unequal resistances. The Ratio Self-Calibration includes an additional test with a voltage divider comprised of 75 Ω and 25 Ω resistors.

Reconfiguration of the circuit for the different test steps is achieved using electronically controlled switches—relays and integrated-circuit switches—which allow the tests to be operated automatically.

One might ask whether ratios above 1 should also be tested. The digital thermometry bridge actually always measures resistance ratios between 0 and 1. Resistance ratio measurements above 1 are produced by simply exchanging the numerator and denominator in the ratio calculation. There is no difference between measuring a resistance ratio of 2.0 and measuring a resistance ratio of 0.5 other than the amplifier gain may be different. This can be verified with a complement test.

Zero and complement tests

In some special cases, unexpected measurement error can also occur at resistance ratios near 0 and 1. To thoroughly exercise the digital thermometry bridge, two additional tests should be performed.

A "zero test" evaluates measurement error at a resistance ratio of 0. This is done by connecting the two wires of the R_X input to the same point in the resistance voltage divider. The measurement is then compared to the ideal value of 0.

A "complement test" evaluates measurement error at resistance ratios near 1. This uses two resistances that are approximately equal. The R_X input is connected to the first resistor and the R_S input is connected to the second resistor. The resistance ratio (approximately 1) is measured. Then the connections are exchanged and the resulting resistance ratio is measured. Ideally, the second measurement should be the reciprocal of the first, and multiplying the two measurements should yield a value of exactly 1. The difference from 1 will be twice the error of a single measurement.

The Ratio Self-Calibration process

A total of eight tests comprise the Ratio Self-Calibration process, which are summarized as follows:

1. **Zero test:** R_X is a perfect short circuit, and R_S is 100 Ω. The test is done twice (step (a) and step (b)), and the two measurements are combined by calculating the mean.
2. **Complement test:** R_X and R_S are both approximately 100 Ω. Their ratio is measured (step (a)). Then they are exchanged and the reciprocal ratio is measured (step (b)). The

measurements are combined by multiplying the two measurements. The error is calculated by subtracting 1 and dividing by two.

3. **Equal ratio sum, 100%:** A 100 Ω / 100 Ω resistance voltage divider is connected. The gain is set to drive the ADC at 100% of full-scale. In step (a) the R_X input is connected to the upper resistor and the R_S input is connected across the network. In step (b) the R_X input is connected to the lower resistor. The measurements are combined by adding the two values. The error is calculated by subtracting 1.
4. **Equal ratio sum, 90%:** This is the same as test 3 but with the gain set at 90% of full-scale.
5. **Equal ratio sum, 75%:** This is the same as test 3 but with the gain set at 75% of full-scale.
6. **Equal ratio sum, 60%:** This is the same as test 3 but with the gain set at 60% of full-scale.
7. **Equal ratio sum, 50%:** This is the same as test 3 but with the gain set at 50% of full-scale.
8. **Unequal ratio sum:** A 75 Ω / 25 Ω resistance voltage divider is connected. (The gain is set to drive the ADC at 100% of full-scale.) In step (a) the R_X input is connected to the 75 Ω resistor and the R_S input is connected across the network. In step (b) the R_X input is connected to the 25 Ω resistor. The measurements are combined by adding the two values. The error is calculated by subtracting 1.

The calibration system itself may contain errors due to drift of the test resistors and stray conductance, electrical interference, capacitance, and measurement noise in the electronic circuits. The effects of resistor temperature coefficients are very small because the resistors are maintained at a constant temperature using a heating device and temperature sensor. The effects of stray conductance and electrical interference are also miniscule by design. The effect of circuit capacitance is limited by allowing adequate settling time before the ADCs are sampled. The dominant component of test uncertainty is measurement noise. To reduce the effect of noise, many measurements are collected, and the mean is calculated. Estimated uncertainties for several representative tests are listed in Table 1.

Table 1. Ratio Self-Calibration uncertainties

Component	Ratio sum, 100% gain	Ratio sum, 50% gain	Zero	Complement
resistor drift	1×10^{-9}	1×10^{-9}	0	1×10^{-9}
stray conductance	2×10^{-9}	2×10^{-9}	0	2×10^{-9}
interference	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}
capacitance	2×10^{-9}	2×10^{-9}	5×10^{-9}	1×10^{-9}
measurement noise	3.1×10^{-8}	4.2×10^{-8}	1.0×10^{-8}	1.1×10^{-8}
combined ($k = 2$)	6.2×10^{-8}	8.4×10^{-8}	2.3×10^{-8}	2.3×10^{-8}

Comparison of calibration methods

Calibrations were performed on a typical digital thermometry bridge using both the RBC device and the Ratio Self-Calibration system.

The RBC calibration used Aeonz model RBC400 and a 100 Ω fixed resistor. The calibration included 35 resistance ratios ranging from 0.3 to 4.0. The time to perform the test was 2 hours and 16 minutes. The results are shown in Figure 3. The graph plots the relative errors (error divided by the resistance ratio, expressed in parts-per-million) versus resistance ratio. The error bars represent estimated expanded uncertainties (k = 2) of the measurements. The overall standard deviation of the measured errors was 0.044 ppm.

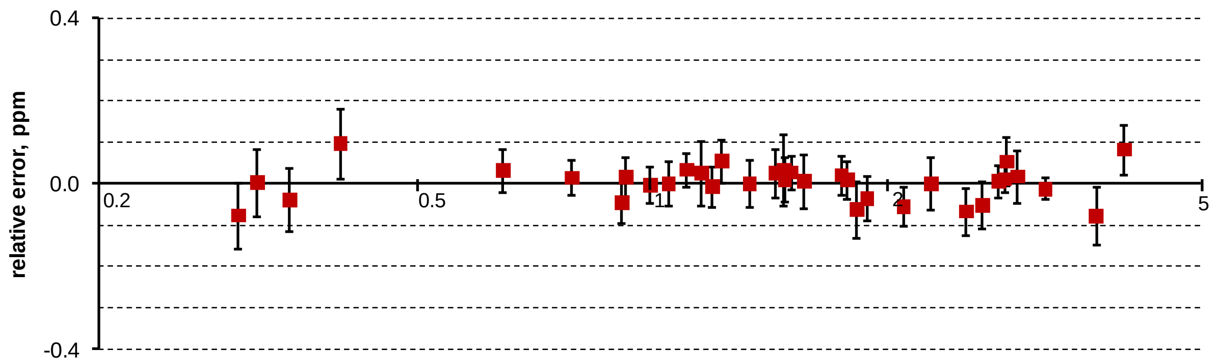

Figure 3. Calibration results using the RBC

The same digital thermometry bridge was also tested using the Ratio Self-Calibration method. The measurement time for each test step ranged from 1 to 3 minutes, as necessary to achieve the required uncertainties (Table 1). The total calibration time was 34 minutes. The results are shown in Table 2. Though the tested resistance ratios are different for the two types of calibration, the maximum magnitudes of the errors are similar.

Table 2. Calibration results using Ratio Self-Calibration

	mean (a)	mean (b)	combined	error (10^{-6})
1. Zero	-0.00000003	-0.00000003	-0.00000003	-0.03
2. Complement	0.99984357	1.00015645	1.00000000	0.00
3. Equal ratio-sum, 100%	0.49996091	0.50003913	1.00000004	0.04
4. Equal ratio-sum, 90%	0.49996094	0.50003912	1.00000006	0.06
5. Equal ratio-sum, 75%	0.49996088	0.50003914	1.00000002	0.02
6. Equal ratio-sum, 60%	0.49996091	0.50003906	0.99999997	-0.03
7. Equal ratio-sum, 50%	0.49996084	0.50003907	0.99999991	-0.09
8. Unequal ratio-sum	0.75003171	0.24996828	0.99999999	-0.01

Tests with defective bridges

The author of this paper (and designer of the digital thermometry bridge) submits that any conceivable failure that introduces significant measurement error will produce an observable error in at least one of the Ratio Self-Calibration tests. To substantiate this claim, several defective thermometry bridges were tested. Defects were intentionally introduced by altering the electronic components and circuits in various ways. The types of problems that were examined include ADC nonlinearity, amplifier nonlinearity, amplifier input conductance, switch leakage conductance, and circuit isolation conductance. Results of the tests are presented in Tables 3 through 6. When compared to the results in Table 2, the defects are obvious. Other tests were also performed, with similar results.

Conclusion

Testing of the Ratio Self-Calibration system indicates that the method is very effective in revealing unexpected resistance ratio measurement errors due to defects in a digital thermometry bridge. The linearity calibration method has several advantages in that it requires no special equipment, operates automatically, and is relatively fast. It facilitates regular and frequent calibration of the thermometry bridge to ensure that accuracy is maintained.

Table 3. Calibration results from a bridge with amplifier and ADC nonlinearity

	mean (a)	mean (b)	combined	error (10^{-6})
1. Zero	-0.00000002	-0.00000003	-0.00000003	-0.03
2. Complement	0.99983910	1.00016094	1.00000001	0.01
3. Equal ratio-sum, 100%	0.49996138	0.50004186	1.00000324	3.24
4. Equal ratio-sum, 90%	0.49996158	0.50004205	1.00000363	3.63
5. Equal ratio-sum, 75%	0.49996193	0.50004246	1.00000439	4.39
6. Equal ratio-sum, 60%	0.49996246	0.50004290	1.00000536	5.36
7. Equal ratio-sum, 50%	0.49996306	0.50004352	1.00000658	6.58
8. Unequal ratio-sum	0.75001819	0.24998526	1.00000345	3.45

Table 4. Calibration results from a bridge with amplifier input conductance

	mean (a)	mean (b)	combined	error (10^{-6})
1. Zero	-0.00000003	-0.00000004	-0.00000004	-0.04
2. Complement	0.99983905	1.00016096	0.99999998	-0.01
3. Equal ratio-sum, 100%	0.49995895	0.50003942	0.99999837	-1.63
4. Equal ratio-sum, 90%	0.49995890	0.50003937	0.99999827	-1.73
5. Equal ratio-sum, 75%	0.49995887	0.50003938	0.99999825	-1.75
6. Equal ratio-sum, 60%	0.49995896	0.50003945	0.99999841	-1.59
7. Equal ratio-sum, 50%	0.49995897	0.50003942	0.99999839	-1.61
8. Unequal ratio-sum	0.75001684	0.24998256	0.99999940	-0.60

Table 5. Calibration results from a bridge with switch leakage conductance

	mean (a)	mean (b)	combined	error (10^{-6})
1. Zero	-0.00000875	-0.00000875	-0.00000875	-8.75
2. Complement	0.99985176	1.00016600	1.00001774	8.87
3. Equal ratio-sum, 100%	0.49996143	0.50004054	1.00000197	1.97
4. Equal ratio-sum, 90%	0.49996139	0.50004048	1.00000187	1.87
5. Equal ratio-sum, 75%	0.49996138	0.50004057	1.00000195	1.95
6. Equal ratio-sum, 60%	0.49996141	0.50004058	1.00000199	1.99
7. Equal ratio-sum, 50%	0.49996134	0.50004054	1.00000188	1.88
8. Unequal ratio-sum	0.75002086	0.24998036	1.00000122	1.22

Table 6. Calibration results from a bridge with circuit isolation conductance

	mean (a)	mean (b)	combined	error (10^{-6})
1. Zero	0.00000125	0.00000127	0.00000126	1.26
2. Complement	0.99984746	1.00015256	1.00000000	0.00
3. Equal ratio-sum, 100%	0.49996311	0.50004027	1.00000338	3.38
4. Equal ratio-sum, 90%	0.49996317	0.50004021	1.00000338	3.38
5. Equal ratio-sum, 75%	0.49996316	0.50004028	1.00000344	3.44
6. Equal ratio-sum, 60%	0.49996315	0.50004027	1.00000342	3.42
7. Equal ratio-sum, 50%	0.49996316	0.50004031	1.00000347	3.47
8. Unequal ratio-sum	0.75001876	0.24998272	1.00000148	1.48

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