

AccuBridge™ A SELF CALIBRATING DC CURRENT COMPARATOR RESISTANCE BRIDGE

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ABSTRACT: An optimized room temperature resistance bridge (AccuBridge™), modeled after the cryogenic current comparator, has been developed to determine current ratio's with the highest accuracy. The direct current comparator has been optimized to reduce the leakage effects of the comparator. In addition, new self calibrating direct current sources have been fabricated and tested. AccuBridge™ relies on self calibrating current sources, the self calibrating direct current comparator and self calibrating nanovoltmeter to achieve its accuracy.

AccuBridge™ makes use of its self-calibrating direct-current-comparator to measure and compare accurately the ratio of the two resistors. A detailed description of AccuBridge™ is presented with an analysis of its accuracy limitations with accuracies < 0.02 ppm and noise levels of <0.005 being achievable.

The bridge is particularly suited to the scaling of resistance standards from 100KΩ down to 0.1Ω at the primary level, while offering a method for providing directly traceable ratio calibrations of less accurate current comparator resistance ratio bridges.

Keywords: AccuBridge, room temperature, self calibrating current sources

1. INTRODUCTION

The measurement of four terminal resistors, using the DC Current Comparator, with better than sub ppm accuracy has been facilitated by the development of the Quantum Hall Resistance System (QHR) and Cryogenic Current Comparator (CCC).

DC current comparator bridges, which have been in service for 40 years, can be used to measure resistors

from a fraction of an ohm to several hundred ohms. The self balancing dc comparator is the main component of these bridges which uses a current source for the master supply and a voltage source for the slave supply. The currents from the power supplies are periodically reversed to eliminate thermal EMFs. Fig 1 shows the dc comparator used in the bridge. Two cores of high-permeability material are driven into saturation by a magnetic modulator. When DC flows through the winding N_x , the signal at the input to the peak detector contains even harmonics of the modulation frequency. This signal is converted to DC by the peak detector which consists of a dc path and an AC path which is proportional to the ampere turns for balancing the comparator. An unbalance in the detector core causes a current to flow through the winding N_s to reduce the net ampere turns in the windings. The output of the peak detector is summed with the slave power. Thus the self-balancing comparator performs like a current transformer which operates at DC and R_x is calculated as follows:

$$1. \quad R_x = R_s(N_x/N_s)$$

The resistors to be compared R_x and R_s are connected as shown in Figure 1. Current from the master power supply I_x flows through the adjustable number of turns N_x and through the resistor R_x . Current from the slave power supply flows through the fixed number of turns N_s and through resistor R_s . At balance the ratio of the currents I_x/I_s is the same as the ratio of the number of turns and of the resistors as indicated in equation 1. This is a double balance bridge and at balance the resistance ratio is equal to the turn's ratio. However, the accuracy is limited to 0.1 ppm with standard deviations of about the same magnitude.

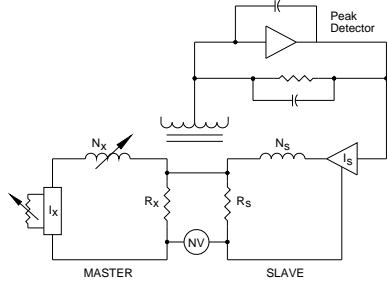


Figure 1
Block Diagram of DC Resistance Bridge

2. OPERATING PRINCIPLE

In the AccuBridge™ principle several improvements have been made to the DC Comparator discussed above. Based on the DC Current-comparator principle with magnetic modulator, it uses two digitally driven current sources with linear ramping circuits to provide the master and slave currents. The main advantage of the ramping current source is that both current sources can be controlled to reverse at the same time effectively reducing the noise in the comparator caused by core & current mismatch and transients. The current sources are periodically reversed to remove the thermal EMFs. A block diagram of the AccuBridge™ principle is shown in Fig 2.

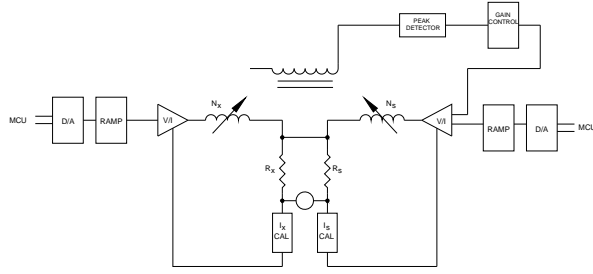


Figure 2
AccuBridge™ Block Diagram

Both the master and slave current source will create the currents controlled using 16 bit digital-to-analog converters with a specific integrated circuitry to complete the required ramping feature. The master current source only produces a master current for the operation using a voltage-to-current converter. The slave current source has a similar functional circuit to supply the slave current, except for having a feedback path from the peak-detector of the current comparator. However, the AC response path has been eliminated decreasing the alternating components in the ratio windings improving the overall noise level present in the comparator further reducing the noise.

Figure 3 shows the performance of the system operation of the current sources under the $R_x=R_s=1K\Omega$ load at

1mA. Two control signals, V_{mc} in the blue trace and V_{sc} in the yellow trace give a closed ramping signal as expected. The green (at V_{mo}) and purple (at V_{so}) signals show the performance of the pre-voltage in the slave and master sources, respectively.

Each current source is calibrated to better than 100 ppm at the beginning of each measurement. As a result, the peak detector is not overloaded due to high ampere turn unbalance due to a mismatch of the current sources. This insures that the rough balance of the resistors under test is within 100 ppm of each other.

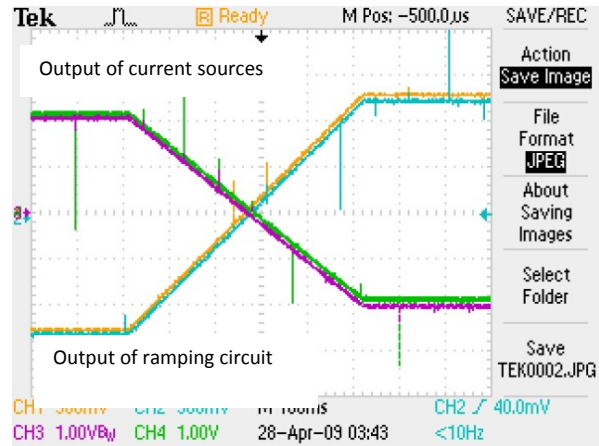


Figure 3
Waveforms for the system operation ($I_x=1mA$, $R_s=R_x=1K\Omega$)

As a result, the effective modulator noise was significantly reduced by:

1. Eliminating the fast feed forward ac path and replacing this with an accurate current source on the slave winding.
2. Decreasing the overall number of turns to increase the resistance range and decrease the leakage paths.

2.1 DC Comparator

The DC comparator has several windings on both the Master and Slave windings. By keeping the reversing transients and core noise as low as possible the number of turns can be reduced for different measurements. The AccuBridge™ principle uses a direct current comparator where the primary and secondary turns are wound in binary. As a result, inter-winding accuracy or linearity verification can be easily verified. Table 1 shows typical results of the DC Comparator where $1 \text{ uat} = 0.01 \text{ ppm}$. The first calibration is of the partial turns verses one real turn. The errors are

stored in memory and added to the ratio when the turns are selected.

1 RT vs 128 PTs : 0.00077 +/- 0.00324 ppm

| | | |
|------|----------|-----------------|
| #1: | 0.00026 | +/- 0.00378 ppm |
| #2: | 0.00070 | +/- 0.00352 ppm |
| #3: | 0.00022 | +/- 0.00306 ppm |
| #4: | 0.00056 | +/- 0.00589 ppm |
| #5: | 0.00077 | +/- 0.00311 ppm |
| #6: | -0.00025 | +/- 0.00405 ppm |
| #7: | -0.00012 | +/- 0.00380 ppm |
| #8: | -0.00035 | +/- 0.00379 ppm |
| #9: | -0.00002 | +/- 0.00323 ppm |
| #10: | 0.00092 | +/- 0.00339 ppm |
| #11: | -0.00252 | +/- 0.00471 ppm |
| #12: | 0.00643 | +/- 0.00752 ppm |
| #13: | -0.00024 | +/- 0.00401 ppm |
| #14: | 0.00120 | +/- 0.00331 ppm |

Table 1
Real Turns Comparison

2.2 Fractional Turns

The AccuBridge™ principle uses an advanced design to eliminate all errors in the fractional turns. The weight of the fractional turns is equivalent to 1/128. The fractional turns are faster and more accurate than a 16 bit A/D. A resistive divider and unloading circuit are used to generate the fractional turns. A 20 bit A/D is then used to make up the residual to give better than 25 bit performance. The A/D acts as a null detector for the last few ppm.

| | |
|-----|------------------------|
| #1: | -0.0004 +/- 0.0029 ppm |
| #2: | -0.0002 +/- 0.0033 ppm |
| #3: | 0.0001 +/- 0.0035 ppm |
| #4: | 0.0001 +/- 0.0043 ppm |
| #5: | -0.0009 +/- 0.0029 ppm |
| #6: | 0.0005 +/- 0.0037 ppm |
| #7: | -0.0005 +/- 0.0035 ppm |

Table 2
Fractional Turns Comparison

3. LEAKAGE CURRENTS

The ratio of resistances can be affected by these leakage currents so it is important to know where and what they are. A 10^{12} leakage pass across R_x will result in a 0.01 ppm error in ratio for a 10k measurement. The possible paths for leakage currents are shown in Fig 4. Each of these leakage paths is in parallel with the I_x or I_s current conductor through which each current flows. Leakage paths across R_x or R_s to ground are considered to be part of the resistor itself as long as the resistor is

known. Resistance substitution method can be used for the higher values as long as the higher value resistor is known. The leakage path from N_s and N_x to ground is by far the most important. The effect of the leakage path can be greatly reduced by keeping the resistance winding as low as possible and by providing proper insulation and positioning of the windings in the comparator.

Leakage paths across R_s produce a positive error and leakage paths across R_x produce a negative error in the indicated value of R_x . The magnitude of the error can be determined by interchanging nominally equal value resistors at 1k Ω and 10k Ω resistances and calculating the offset. The leakage error of the resistance path was measured and is in the order of 10^{13} Ω . The internal supplies of 30V can be used to intercompare 100k Ω to 10k Ω to a resolution of 0.001 ppm. This can be performed at a current of 0.1 mA in R_x or 10 mW of power in R_s (10k Ω)

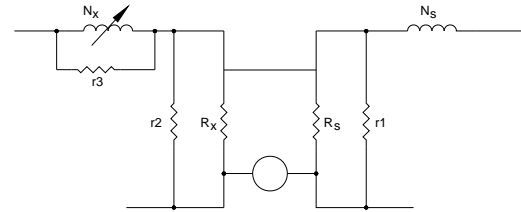


Figure 4

Leakage Paths of the
DC Current Comparator

For 10:1 measurements, the leakage errors can also be determined by performing interchange, 10:1 and 1:10 measurements and calculating the offset as shown in table 2. This can only be accomplished by using the AccuBridge™ principle which is used to reduce the leakage errors on the N_s & N_x windings. The leakage path r_1 and r_2 are greatly reduced by using proper wiring and proper terminal washers. The current which flows through R_s and r_1 can be summarized as follows:

$$2. \quad R_x = (R_s / r_1) \times (N_x / r_2) / N_s$$

4. TEST RESULTS

The prototype has been tested for about 6 months now. Units have been shipped to a few National Laboratories for evaluation and some results have come in. The standard deviation at the bridge shows definite improvement over the older technology. A 1:1 in house intercomparison is listed in Table 3. For 10:1 measurements the AccuBridge™ principle was compared to our calibrated bridge. Errors and standard deviation are shown in Table 4. Thirty-five (35)

measurements are made with the last twenty-five (25)
being used for statistics.

| Resistors ohms | Ix mA | Settle Time (sec.) | Filter Sec. | ----- FORWARD----- | | ----- REVERSE----- | | Inter Error (ppm) |
|-------------------|----------|--------------------------|----------------|-----------------------|-------------------|-----------------------|-------------------|-------------------------|
| | | | | Measured Ratio | Std Dev ppm | Measured Ratio | Std Dev ppm | |
| 1:1 | 31.6 | 12 | 0.3 | 1.000042417 | 0.01 | 0.999957595 | 0.00 | 0.01 |
| 1:1 | 31.6 | 12 | 0.3 | 1.000042430 | 0.01 | 0.999957582 | 0.00 | 0.00 |
| 10:10 | 10 | 12 | 0.3 | 0.999996134 | 0.00 | 1.000003863 | 0.00 | 0.00 |
| 10:10 | 10 | 12 | 0.3 | 0.999996125 | 0.00 | 1.000003872 | 0.00 | 0.00 |
| 100:100 | 3 | 12 | 0.3 | 1.000021302 | 0.00 | 0.999978694 | 0.00 | 0.00 |
| 100:100 | 3 | 12 | 0.3 | 1.000021313 | 0.01 | 0.999978680 | 0.00 | 0.00 |
| 1k:1k | 1 | 16 | 0.3 | 1.000119449 | 0.01 | 0.999880543 | 0.01 | -0.01 |
| 1k:1k | 2 | 12 | 0.3 | 1.000119479 | 0.01 | 0.999880517 | 0.01 | -0.01 |
| 1k:1k | 3 | 12 | 0.3 | 1.000119475 | 0.01 | 0.999880543 | 0.00 | 0.00 |
| 1k:1k | 4 | 12 | 0.3 | 1.000119458 | 0.01 | 0.999880555 | 0.00 | 0.00 |
| 1k:1k | 5 | 12 | 0.3 | 1.000119423 | 0.01 | 0.999880591 | 0.00 | 0.00 |

Table 3
1:1 Interchange Measurements

| R ohms | Run # | Current Ix mA | Settle Time sec. | -----Reference 6010----- | | | -----UUT 6010D----- | | |
|-----------|---------|------------------|---------------------|--------------------------|----------------|-------------------|---------------------|----------------|----------------------|
| | | | | Measured Ratio | Ratio Error | Absolute Ratio | Measured Ratio | Std Dev ppm | Ratio Error (ppm) |
| 10:1 | 1 | 5.0 | 8 | 10.006161484 | -0.00000036 | 10.00616184 | 10.0061615 | 0.0021 | -0.03 |
| | 2 | | | 10.006161652 | -0.00000036 | 10.00616201 | 10.006161620 | 0.001 | |
| | 3 | | | 10.006161424 | -0.00000036 | 10.00616178 | 10.006161692 | 0.001 | |
| | Average | | | 10.00616152 | -0.00000036 | 10.00616188 | 10.00616160 | 0.002 | |
| | | | | | | | | | |
| 100:10 | 1 | 3.0 | 8 | 9.993469918 | 0.00000012 | 9.99346980 | 9.9934695 | 0.0021 | -0.02 |
| | 2 | | | 9.993469907 | 0.00000012 | 9.99346979 | 9.993469600 | 0.003 | |
| | 3 | | | 9.993469843 | 0.00000012 | 9.99346972 | 9.993469484 | 0.002 | |
| | Average | | | 9.99346989 | 0.00000012 | 9.99346977 | 9.99346953 | 0.002 | |
| | | | | | | | | | |
| 1k:100 | 1 | 2.0 | 8 | 10.000207616 | 0.00000003 | 10.00020759 | 10.000207310 | 0.005 | -0.03 |
| | 2 | | | 10.000207628 | 0.00000003 | 10.00020760 | 10.000207250 | 0.002 | |
| | 3 | | | 10.000207542 | 0.00000003 | 10.00020751 | 10.000207250 | 0.007 | |
| | Average | | | 10.00020760 | 0.00000003 | 10.00020757 | 10.00020727 | 0.005 | |
| | | | | | | | | | |
| 10k:1k | 1 | 0.3 | 8 | 9.999841174 | -0.00000042 | 9.99984159 | 9.999841440 | 0.002 | -0.02 |
| | 2 | | | 9.999841118 | -0.00000042 | 9.99984154 | 9.999841420 | 0.002 | |
| | 3 | | | 9.999841087 | -0.00000042 | 9.99984151 | 9.999841315 | 0.002 | |
| | Average | | | 9.99984113 | -0.00000042 | 9.99984155 | 9.99984139 | 0.002 | |
| | | | | | | | | | |

Table 4
10:1 Ratios

5 CONCLUSIONS

It has been shown that there are advantages of ramping and switching the current sources and removal of the AC path. It has been known in the old design that the modulation and line frequency is amplified and fed back into the comparator through the slave winding. Removal of the AC path has lowered the standard deviation of the measurements. Ramping and switching of the currents have improved the interchange errors. The technology is suitable for measuring 1:1 ratios with a ratio accuracy of 0.01 ppm and 10:1 ratio's from 1Ω to $10k\Omega$ and $100k\Omega$ with slightly reduced accuracy which needs to be investigated further. The noise level in all cases was less than the quoted standard deviation of <0.02 ppm.

The bridge has been in development for about 6 months for the measurement of decade resistors. It is easy to use, the IEEE488 interface making it ideal for recording the measurements runs. However, further investigation is required to improve the accuracy for the 10:1 ratio's to be below 0.02 ppm.

6. REFERENCES

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