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Application Note

The Lake Shore Model 370 AC Resistance Bridge[1] and its Matched Impedance Current Source

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Introduction

Very low temperature resistance measurements have been plagued for years with the dual problems of self-heating and measurement error due to the measurement system converting common-mode noise to differential-mode noise. This application note focuses on the patented Lake Shore solution to this very real problem associated with low temperature, high resistance (and low heat capacity) measurements. First let us present the problem and then the solution.

Problem: The Single-Ended (Unbalanced) Current Source

Traditional ac bridge current source design is based on a single-ended current source referenced to a measurement ground. Given a noise-free environment, this topology works well. If we introduce environmental noise into the picture, however, problems arise which are difficult to detect and quantify, and even more difficult to eliminate.

Environmental noise can come from many sources and at many frequencies, but almost all measurements must deal with 50/60 Hz related noise components from mains power. It is desirable to reduce the coupling of these signals as much as practical by appropriate wiring and shielding techniques. In many cases, this is still not enough to resolve all issues, but why? The answer lies in the inherent inability of the single-ended, grounded current source to reject common-mode environmental noise.

Assume a 100 kΩ resistor attached to a single-ended current source. What impedance does the grounded end of the resistor offer to environmental noise? From a practical standpoint, this impedance is 0 Ω. Similarly, what is the impedance offered to environmental noise on the current source driven end of the resistor? This impedance would be the parallel combination of the resistor itself and the output impedance of the current source. If the current source is reasonably well designed, that is, its output impedance approaches infinity, then the parallel combination remains 100 kΩ to environmental noise on the driven side of the resistor.

Clearly, there is an extreme difference in impedance as seen at the nodes on each side of the resistor being measured.

If environmental noise is coupled equally to both ends of the resistor through equal impedances (common-mode coupling), the consequence of the coupling is radically different at each end of the resistor. Voltage variation at the grounded end is minimal, since its presented impedance is virtually 0 Ω. The driven end of the resistor, however, varies as freely as 100 kΩ will allow to the coupled noise and its source impedance. This topology (the grounded source) inherently converts common-mode environmental noise to differential-mode noise directly across the resistor. Once this is done, the noise cannot be separated from the desired signal across the resistor except in regard to frequency differences between the noise and the differential-mode signal from the current source.

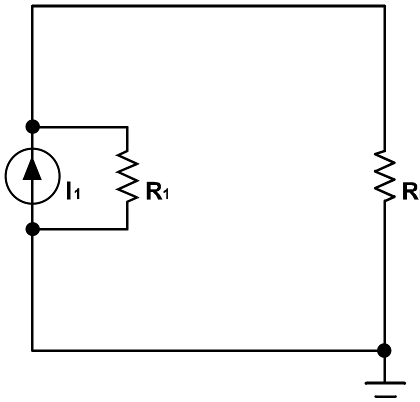

Figure 1a

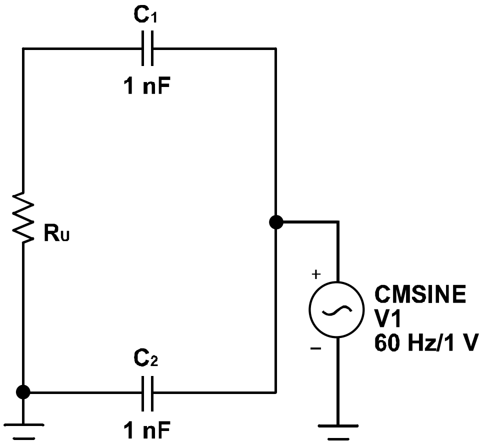

Figure 1b

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[1] *Actually, calling this a bridge is a misnomer – It is not a bridge in the conventional sense. Although the Model 370 drives the resistive temperature device (RTD) in a "bridging" fashion (differential drive from two sources) it does* ***not*** *place the RTD in a traditional, null-sensing, bridge configuration. It directly applies a current through the RTD and directly measures the resultant voltage across the RTD using lock-in techniques. The term "bridge" is retained to best reflect the intended use of the Model 370 in a functional sense.*

Neglecting the effect of external filtering, even the use of a high quality, balanced instrument amplifier will not resolve this contamination regardless of the common-mode rejection ratio (CMRR) of the instrument amplifier by itself. A second consequence is the resultant current through the 100 kΩ resistor from the common-mode induced noise signal. In cryogenic applications where the 100 kΩ resistor is actually an RTD, this topology can cause self-heating of the sensor and therefore, erroneously cause high temperature readings compared to the actual temperature of the sensor's surrounding environment.

An equivalent circuit representation of this topology (Figure 1a) easily shows the associated problems. I_1 and R_1 represent the current source (Norton equivalent) of the traditional ac bridge. Notice that it is connected to ground (measurement common) making this current source "single-ended" or unbalanced. For the sake of the discussion that follows, the output value of this current source is set to 0 A (hence eliminated from our circuit) since we are concerned with the reaction of this topology to common-mode signals and not to the differential-mode ac current used to measure the resistor. Likewise, the current source output impedance (R_1) approaches infinity at low frequencies and can also be ignored. R_U represents an RTD deep within a cryostat in a low temperature environment.

The removal of I_1 and R_1 simplifies the circuit to a resistor with one end grounded. Figure 1b shows the resistor R_U together with an equivalent circuit for coupling common-mode environmental noise. Common-mode environmental noise couples to both ends of R_U through C_1 and C_2.

C_1 and C_2 represent capacitive coupling of a noise voltage source to both ends of R_U, similar to the environmental coupling resulting from cable capacitance of shielded cables (easily 1 nF) that have shields terminated at a location different than measurement common (perhaps the cryostat case) while the current source measurement common is tied to power line ground (frequently done in traditional ac bridge designs.) In this instance the cryostat should ideally be tied to power line ground to minimize this difference in ground potential. In reality, there is some difference in noise voltage between the cryostat and the measurement common. For the sake of the simulation, 1 V at 60 Hz is assumed to be the difference between the two. 1 V is not an unreasonable level; as much as 10 V is sometimes observed experimentally. With C_2 shorted to ground, the noise voltage across R_U (the RTD) can be expressed by voltage division as

$$\mathbf{V_{R_U} = [R_U/(R_U + 1/j\omega C_1)]V_1 = [1/(1 + 1/j\omega C_1R_U)]V_1}$$

With R_U at 100 kΩ and V_1 at 1 V/60 Hz, the resulting voltages and powers for various values of C_1 are given in Table 1.

The resultant noise powers are certainly enough to significantly heat the RTD causing error in temperature readings at low temperatures. Under this circumstance, how does one know whether the sensor is self-heating and if so, by how much? Operating the ac bridge at a lower excitation does *not* solve this problem since the offending excitation is coming from outside the bridge electronics. If the voltage measurement is filtered by a band pass filter at the excitation frequency of the ac bridge, the 60 Hz noise excitation may not be observed. Sometimes, the unknown is measured as a function of excitation, and a deviation from linearity is observed; this deviation is associated with self-heating from excitation power and not associated with noise corrupting the measurement.

C_1	$\omega C_1 R_U$	V_{R_U} in mV	P_{R_U} in nW
1 nF	0.0377	37.7	14.3
2 nF	0.0754	75.2	56.5
5 nF	0.1885	185.2	343
10 nF	0.3770	352.8	1244

Table 1

A high-impedance instrument amplifier is normally used to measure the voltage across R_U. This amplifier will read differential voltage across R_U and ignore the common-mode voltage of R_U. It is important to understand that the topology of the single-ended current source automatically *converts* common-mode noise to differential-mode (differential) voltage across the RTD. At that point the damage is done, and the best instrument amplifier in the world simply cannot resolve between two separate sources of differential-mode signals unless they are separated in frequency. Although lock-in amplifier techniques reduce the sensitivity to the environmentally coupled noise in the electrical part of the measurement substantially, the fact remains that self-heating of the RTD from the noise source is still present. There is a solution**…**

Solution – The Matched Impedance (Balanced) Current Source

Let us take the circuit of Figure 1 and add a complementary current source mirroring the first in magnitude but having opposite polarity (Figure 2.)

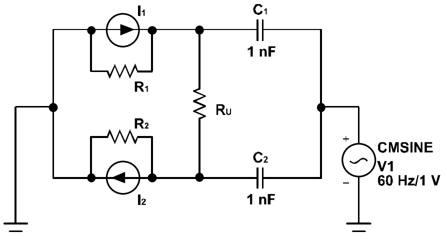

Figure 2

I_2 and R_2 have been added so that each end of R_U is now driven by a current source. From an ideal perspective, both current sources have output impedances that approach infinity. By superposition, that is, with I_1 and I_2 at zero current, we can again illustrate the circuit of Figure 2 for noise measurements alone, as shown in Figure 3.

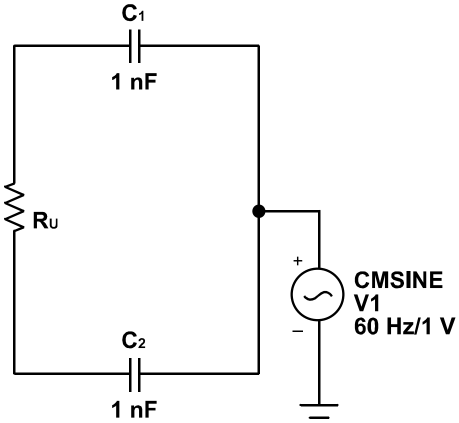

Figure 3

We immediately observe the major difference that the balanced current source has created. The *ground* to R_U is no longer present, that is, there is no return path for the noise source. Consequently, it is unable to generate any noise across R_U, no matter the values of C_1 and C_2. In fact, they do not have to be equal, since all the noise source can do is move them up and down equipotentially with respect to its ground. Unfortunately, this is not the whole story. We do have to connect the bridge to a real experiment, and in that case we have to modify our simple noise circuit once more.

Effect of the External Wiring Environment

Depending on the actual environment, there can be significant wiring impedances to ground from each side of our unknown resistor, R_U. Cable capacitance is the major contributor to these impedances. These are depicted in Figure 4 as C_3 and C_4.

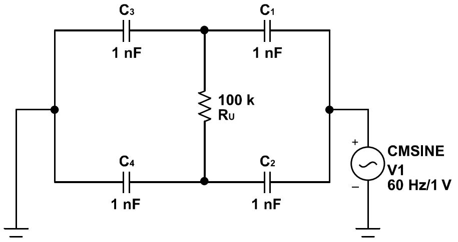

Figure 4

These two paths to ground degrade the instrument common-mode rejection performance unless each pair of impedances is matched or their cross products are equal. The extreme case is where either C_3 or C_4 is large compared to the other three capacitors. This gives us the equivalent of the grounded example of Figure 1b (through the large capacitor) and we are once again converting the majority of the common-mode noise to a differential-mode signal with its magnitude dependent on voltage division. How can this example exist experimentally? One example is to use a long coaxial cable for one lead and a short coaxial cable for the other. A more common example would be switching between several unknown resistors and providing a common lead to these unknowns, which could result in a significantly higher capacitance associated with that return path. Normally, however, C_3 would be the same order of magnitude as C_4.

If C_1 equals C_2, then we can plot the effect of an imbalance between C_3 and C_4 and its effect on the common-mode rejection of the experimental arrangement. Again, we ignore the input resistances of the current sources because of their very high values for various values of C_3/C_1. This has been done in Figure 5 for $C_3/C_1 = 0.1$, 1, and 10 with the ratio of C_3/C_4 varying between 0.2 and 5. Obviously, the problem gets more complex if we also allow C_1 and C_2 to vary.

Note that the reduction in the common-mode rejection ratio is not due to the instrument, but is due to the experimental wiring associated with the experimental setup. Fortunately, the Lake Shore Model 370 AC Resistance Bridge can help with this problem.

Guard Drives

The Model 370 AC Resistance Bridge provides guard drive outputs to drive the shields of each of the four leads (used in a four-lead measurement) with a buffered version of the signal that the inner lead is carrying. This reduces the effective cable capacitance (as represented by C_3 and C_4 of Figure 4) to nearly zero. Therefore, the effect of imbalances caused by these capacitances is also substantially reduced. The guard drives are limited to direct connection with the Model 370 itself and are included in the long, triaxial cables provided between the Model 370 and the scanner. Guard drives are *not* available for wiring between the scanner and sensors. It is intended that the scanner be physically positioned close to these sensors to minimize the need for guard drives.

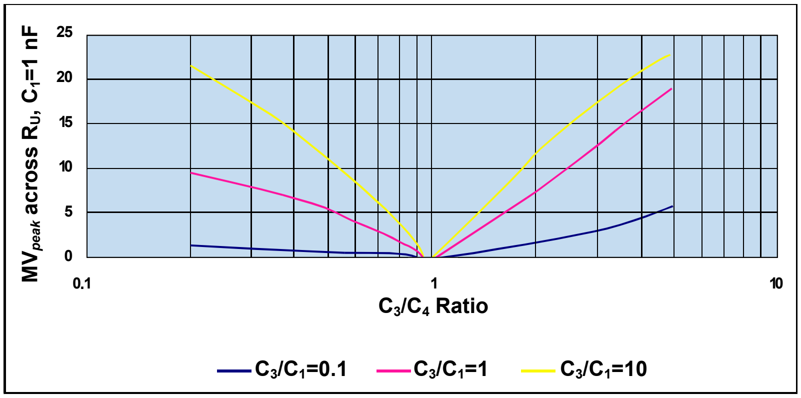

Figure 5

Theory vs. Real Operation

Equivalent circuit analysis certainly shows that a problem exists if common-mode environmental noise is present with a single-ended current source. In practice, this problem is seen frequently. Attachment to a computer interface causes the temperature reading to rise inexplicably. Screen rooms are installed to minimize the existence of capacitively coupled environmental noise. Custom filters are designed to reduce the effect of existing common-mode noise. Work times are scheduled around noisy equipment or nearby radio station operation. A cryogenic system simply fails to achieve an expected temperature. These are all possible symptoms of this basic topology and its inability to reject common-mode noise. It is the writer's conjecture that many installations have errors that are simply not yet identified as common-mode noise issues.

The Lake Shore Model 370 incorporates a patented balanced current source design, which allows an equal (and very high) impedance to be presented to environmental noise from each end of the RTD. As a result, both ends of the resistor respond to environmentally coupled noise in a balanced fashion. This means that common-mode noise *remains* common-mode noise allowing the following instrument amplifier to actually reject the common-mode noise as it was intended to do. The second, and perhaps most important benefit, is that the resistor does *NOT* have current flow through it resulting from environmental noise. Self-heating from environmental noise is consequently reduced substantially and in most cases, below detection level *without* the use of screen rooms, special filters, optical isolation to local computers, etc. This reduces the associated costs in time and materials to correct the problem, and is clearly a significant and timely advantage.

Simulations are useful but how does the Model 370 perform in reality? The values chosen for Figure 3 were applied to a Model 370. The capacitors selected were not matched, but within 5%. In reality, the matching of effective coupling capacitances may not be very close. A sine wave generator at 100 Hz was set up to provide the common-mode noise voltage V_1 in Figure 3. Cables were of equal length (3 ft) but no special attention paid to matching them. With a ground line to one side of R_U (to effectively simulate unbalanced operation) the common-mode sine source was turned up until the output of the Model 370 instrument amplifier (×1000 gain) = 10 V_{peak}. This level indicates that there was 10 mV_{peak} across R_U or 1 nW_{peak}. When the ground was released and the Model 370 allowed to work as designed, the instrument amplifier output dropped to 40 mV_{peak} indicating 40 μV_{peak} across the resistor, dropping the power across the resistor to 16 fW_{peak}. This is a –48 db improvement in voltage across R_U and a massive –96 db improvement in power across R_U.

The test was repeated with one of the 1 nF capacitors replaced by a 5 nF capacitor to see whether there was still an advantage with extremely imbalanced coupling of common-mode noise signals. In this case, the improvement was not as great (as expected) but still resulted in a –26 db improvement in voltage across R_U and a substantial –52 db reduction in power dissipated across R_U from the common-mode source.

A test with 10-megohm resistors replacing C_1 and C_2 yielded –50 db voltage and –100 db power reductions. The results using 100-megohm resistors (20% match) was –30 db voltage and –60 db power reductions in R_U related to common-mode noise coupling.

For the record, the Model 370 instrument amplifier exhibits a minimum measured CMRR of –120 db. That means very little if one side of the amplifier is grounded and you are attempting to reject common-mode noise interference. The single-ended current source topology then severely limits your ability to reject common-mode signals in a 4-lead measurement. Your only choice then is to minimize the *existence* of common-mode signals by external means. The Model 370 gives you the measurement topology to make valid measurements in the presence of common-mode noise.

Common-mode Emission Reduced As Well

There is a converse to common-mode noise rejection (susceptibility) that can be thought of as common-mode emission. Just as the grounded current source converts common-mode noise to differential-mode noise, it also emits common-mode noise from the voltage imposed across R_U resulting from normal measurement current through R_U. This is an e-field emission from a grounded reference point and can easily contaminate simultaneous measurements in the same vicinity. It is common to use differing frequencies between two bridges to minimize such cross-coupled errors. Again, the Model 370 resolves this issue.

The resultant voltage across R_U in a balanced system is balanced as well with a resultant e-field of ideally zero, since each end of R_U is equal but opposed in voltage. Cross-coupling between two bridges in the same vicinity is greatly reduced, if not totally eliminated. Even so, the Model 370 is equipped with two alternate operating frequencies for those instances when balanced operation may be compromised.

Isolated Measurement Common

Ground loops are common sources of common-mode noise as discussed in the previous sections. This frequently arises with instruments that share measurement common with the power ground and tie both to the instrument chassis. Once bonded with a cryostat that has its own ground through the myriad of plumbing pieces and associated pumps for mechanical operation, a ground loop of significant current potential can easily exist. Although the Model 370 is excellent at rejecting the common-mode noise resulting from such loops, it is still desirable to eliminate the ground loops and associated currents from an installation, thereby reducing that noise to an absolute minimum.

Established instrument design dictates that the chassis of an instrument be connected to power line ground via the power cord. With that as a given, the Model 370 provides the answer through internal optical coupling of the measurement electronics. The Model 370 measurement common is *not* connected to the power line ground or main chassis. The entire analog measurement circuitry “floats” at whatever potential that is provided to the measurement common of the analog section. Proper installation strongly suggests that the measurement common be connected to the cryostat case by way of a single wire from the case of the scanner (that is measurement common, *not* power ground) and/or measurement cable shields connected at both the scanner end (or the Model 370 if a scanner is not used) and the cryostat or experiment end. If the measurement common of the Model 370 is not tied, there may be increased electrical noise as a result. The potential ground loop is broken by the optical isolation internal to the Model 370 and no current flows to cause noise.

Note: *A 1-megohm resistor exists between the chassis and measurement common to discharge any static buildup in the event that the measurement common is not connected properly. This resistor can be removed if deemed necessary in very sensitive installations.*

The computer interfaces (IEEE-488 and RS-232) are ground referenced to the power line ground. This is tolerable since these signal levels are much higher and the connecting equipment is normally power line referenced as well. Minor currents that may occur here (and a ground loop certainly can occur) are localized to the interface that is designed to handle reasonable noise levels. It does not affect the measurement sections since they are optically isolated.

Isolated Heater Output

The heater output of the Model 370 is electrically isolated from both the power line ground and the measurement common. This allows floating use of the output in grounded heater applications, eliminating unexpected current paths.

Note: *A -megohm resistor also exists here between the chassis and heater common to discharge any static buildup in the event that the heater common is not connected properly. This resistor can be removed if deemed necessary.*

Installation Suggestions

The Model 370 AC Resistance Bridge provides the user with an arsenal of features to best reduce environmental noise issues. Before installation, the wiring should be examined to ensure reasonable electrical balance. A resistance measurement from each of the four leads used in the measurement should be made to ensure little or no resistive leakage to cryostat case or other wiring. Similarly, since we are dealing with an ac measurement, we also need to balance the capacitive elements of the wiring as well. A simple capacitance meter can be used to check the wiring capacitance between each of the four leads and cryostat case (which should also be measurement common). Ideally, the capacitances of all four leads should be similar. For exceptionally long cable runs, the Model 370 has available four guard drives (one for each measurement lead) to reduce the effect of cable capacitance using long triax cables. In the best of installations, the degree of common-mode rejection is proportional to the degree of balance, as determined by wiring practices. Even in the worst of balances, the Model 370 will still reject more environmental noise than the traditional, single-ended current source of other ac bridges.

Note: *If wiring of multiple sensors uses a common lead (to save the running of extra wires), the Lake Shore AC Resistance Bridge cannot offer a noise advantage, since this wiring method requires that the common lead be grounded. The Model 370 will perform well with a grounded lead of the current source but obviously loses the ability to reject common-mode noise due to the externally compromised balance.*

Conclusion

There are many factors that contribute to the accuracy and repeatability of low excitation resistance measurements, especially at resistances over 10 kΩ and low (cryogenic) temperatures. Traditional ac resistance bridge circuit topologies commonly use grounded (or single-ended) current sources. Single-ended current sources allow resistance measurement errors that are frequently difficult to detect and eliminate. The single-ended topology inherently converts common-mode noise induced on resistor leads to differential-mode noise that is difficult to overcome and yet often overlooked as a source of error. The Lake Shore Model 370 AC Resistance Bridge utilizes a patented matched-impedance current source to prevent common-mode noise from being translated to measurement error. This current source combines with other noise reduction features to make the Model 370 less sensitive to environmental noise than any product of its kind.

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Model 370
AC Resistance Bridge

with temperature control

The Model 370 AC Resistance Bridge is designed for precise, accurate, low noise, low excitation power AC resistance measurement. Its primary application is the measurement of resistance materials in cryogenic environments from 20 mK to 1 K. Fully integrated, the Model 370 includes features to reduce and control noise at every step of the resistance measurement process. A unique, patented, matched impedance current source and active common-mode reduction circuitry minimize noise and self-heating errors. With sixteen channels, IEEE-488 and serial interfaces, and closed-loop temperature control, the Model 370 offers seamless integration with existing cryogenic systems and the most complete package on the market today. Used with calibrated Lake Shore subkelvin resistance temperature sensors, the Model 370 not only measures and displays but also controls temperature for dilution refrigerators and other cryogenic systems.

NEW 3716L Scanner for the Model 370

Ideal for Hall measurements of low impedance materials, the 3716L is designed to improve the noise-floor for very low resistance measurement. The 3716L has a lower input noise than the 3716 for resistances less than 100 Ω. It offers a 5x improvement in noise-floor, making it possible to resolve resistance changes of 20 nΩ.

Unique noise-reduction elements:

Patented current source preserves common mode noise rejection

Optically isolated measurement electronics eliminates the potential for ground loops

Features:

Resistance measurement ranges from 2 mΩ to 2 MΩ

Twenty-one excitation levels from 3.16 pA to 31.6 mA

Displays real-time sensor excitation power

PID temperature control

IEEE-488 and RS-232C interfaces, alarms, relays, and analog outputs

Scanner choices:

3716: Adds sixteen channels and is optimized for high resistance sensor performance

3716L: Adds sixteen channels plus provides a 5x lower noise floor for low resistance measurements less than 100 Ω

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