

PPMS Application Note 1584-201

Cause and Effects of Common-Mode Leakage

Performing four terminal voltage measurements at nanovolt levels is always a challenging problem, and the success of such measurements usually depends on one's ability to achieve the requisite signal-to-noise ratio in the electronic detection system. This was an important problem in the design and development of the Quantum Design AC Transport (ACT) option for the PPMS.

The ACT option includes a front end preamp having sub-nanovolt sensitivity, while providing up to two amps of excitation current. Achieving the full preamp sensitivity at the highest drive levels required the use of a number of design features to eliminate inductive and capacitive crosstalk between the drive and detection circuits. These features included the usual standard techniques of using tightly twisted leads, a balanced drive system, and providing separate cabling for the drive and voltage sensing leads.

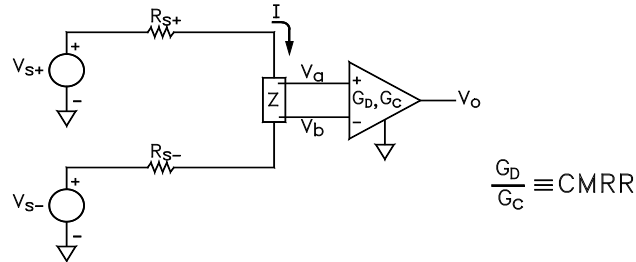
A less obvious source of error that had to be addressed, and which often arises when making nanovolt-level measurements, is called *common-mode leakage*. This effect is not as well known as the issue of signal-to-noise ratio, but when making low power, high sensitivity measurements, common-mode leakage is often the more significant problem. With high sensitivity instruments such as the AC Transport option, common-mode leakage can create measurement artifacts that are difficult to separate from the actual potential difference across the sample. In this technical note we describe how common-mode leakage arises, how it can affect a measurement, and what the knowledgeable experimentalist can do to minimize its effects.

Sample excitation and its effects on common-mode leakage

Figure 1 shows the excitation circuit of the ACT option. It provides current to the sample and is configured as a balanced bi-polar output amplifier. The basic circuit has two voltage sources, V_{S+} and V_{S-} , with two resistors, R_{S+} and R_{S-} , which are in series with the sample to be measured (Z). Ideally, the highly balanced symmetrical drive circuit keeps the voltages at the positive and negative driver outputs equal in magnitude and opposite in sign. For example, if the positive source behind resistor R_{S+} is at -2.4 volts, then the negative source behind the resistor R_{S-} will be at +2.4 volts. The resistances modeled in the drive circuit of **Figure 1** may also be generalized to include capacitive and inductive effects when AC measurements are made at higher frequencies.

The high degree of symmetry in both the excitation sources and their internal impedance is designed to keep the common-mode voltage of the sample, $(V_a + V_b)/2$, as close to zero as possible with respect to ground. This arrangement, called *drive balancing*, helps eliminate false effects produced by common-mode voltages appearing at the voltage contacts on the sample. (In

this case we define the common-mode voltage to be any voltage that appears at both voltage contacts of the sample, as opposed to the voltage difference which is produced by the excitation current.) Common-mode leakage is driven by the common-mode component of the voltage across the sample.



$$\text{Ideal output: } V_{\text{ideal}} = (V_a - V_b) G_D$$

$$\text{True output: } V_o = (V_a - V_b) G_D + \left(\frac{V_a + V_b}{2} \right) G_C$$

Figure 1. Basic circuit diagram of AC Transport Option, configured as a balanced bipolar output amplifier with respect to the sample (Z). $V_a - V_b$ is the potential drop across the sample while $(V_a + V_b)/2$ is the common-mode voltage which appears across the sample.

Voltage sensing and the effects from common-mode leakage

Voltage measurements in the ACT option are made using a differential amplifier (sometimes referred to as an instrumentation amplifier), which detects the potential difference across the voltage terminals. In an ideal differential amplifier, the output voltage is exactly proportional to the voltage difference that appears across its positive and negative terminals, $(V_a - V_b)$, so that any common-mode voltage is completely rejected. In the case of real amplifiers, the extent to which the common mode voltage is rejected is given by the *common-mode rejection ratio* (CMRR), defined as the ratio of differential gain, G_D , to common-mode gain, G_C , and is expressed in decibels.

$$(1) \quad \text{CMRR} = \frac{G_D}{G_C}$$

In practical terms, a CMRR of 120 dB means that the differential voltage across the amplifier inputs receives a factor of 10^6 greater amplification than the common mode signal. Even though high quality differential amplifiers are designed to have very large CMRRs, common mode signals can still seriously affect the high sensitivity measurements made with the ACT option. In such high precision circuits, one can calculate the expected common mode signal according to the following equation.

$$(2) \quad V_o = G_D \left[(V_a - V_b) + \frac{(V_a + V_b)}{\text{CMRR}} \right]$$

Where V_o is the output voltage of the amplifier, V_a and V_b are respectively the voltages at the positive and negative inputs of the amplifier. G_D is the differential gain, and CMRR is the common mode rejection ratio. The second equation clearly shows that the output voltage, V_o , will be proportional to the differential input voltage only while the common-mode leakage

term $(V_a+V_b)/CMRR$ is small compared to the differential term, (V_a-V_b) . Alternatively, the expression can be written with the common-mode term expressed as a fractional error, F , where

$$(3) \quad F = (V_a+V_b)/[(V_a-V_b)CMRR] \ll 1$$

for the common mode leakage to be insignificant.

When the net common mode voltage, (V_a+V_b) , becomes large, or the potential difference across the sample, (V_a-V_b) , is small, the contribution from the common-mode component can become significant, producing a large value of F and leading to errors in the measurement. In fact, if the signs of the common-mode and differential terms happen to be different, and the differential term is very small, the measured voltage can even have the wrong sign, producing an apparent *negative* resistance for the measurement. Since common-mode leakage can occur in any voltage measurement, this effect may appear in all four of the measurements made with the ACT option: AC Resistivity, Hall effect, I-V characterization, and critical current measurements.

Minimizing common-mode leakage

The third equation clearly shows that minimizing fractional error, F , will minimize common-mode leakage. It is clearly advantageous to maximize both (V_a-V_b) and $CMRR$. However, the common-mode rejection ratio of a preamp is normally determined by the components used in the preamp, and the potential drop across the measurement terminals, (V_a-V_b) , is determined by the sample itself. In either case, you cannot easily control these variables during an actual measurement. The obvious way to increase (V_a-V_b) is to increase the excitation current, but since the common-mode voltage also rises with increased excitation, the ratio of the two remains unchanged. Thus, minimizing the common-mode voltage, (V_a+V_b) , is the most attractive means of reducing common-mode leakage.

Minimizing (V_a+V_b) By Balancing The Drive At The Sample

As discussed above, the drive voltages and the resistance in each leg of the drive circuit need to be highly symmetrical to keep the common voltage (V_a+V_b) near ground potential. In the ACT option, the resistances in the excitation drive circuit are carefully matched on the various excitation ranges (**Table 1**).

| Current Range | Resistance R_{s+} | % Variation |
|---------------|---------------------|-------------|
| 200 μ A | 50 k Ω | .2 |
| 2 mA | 5 k Ω | .2 |
| 20 mA | 500 Ω | .2 |
| 200 mA | 50 Ω | .02 |
| 2 A | 5 Ω | .015 |

Table 1. The internal resistances and their variations in one leg of the drive circuit of the ACT for various ranges.

In addition, the internal probe wiring of the PPMS system matches the path lengths for the sample excitation wiring. These provisions are designed to minimize the common-mode voltage contribution from the excitation circuit and instrument wiring. The values of R_{s+} in **Table 1** express the resistance in only one side of the drive circuit.

Common-mode effects can also arise from the sample itself. The most frequent source of common-mode leakthrough associated with the sample arises from contact resistance between the excitation leads and the sample. This is an especially important issue when one is measuring samples extremely difficult to make low-resistance electrical contacts. (High-Tc superconducting samples provide an excellent example here. Making reliable and robust electrical contacts to these materials was a particular problem in many early measurements on HTS materials.)

When the difference in contact resistance between the two excitation leads becomes significant compared to the resistance of the sample, the difference in contact resistance will produce significant common-mode leakthrough. This may be somewhat surprising since using a four-terminal measurement reduces the effects of line interference and lead resistance. However, the contact resistance of the excitation leads simply appears as additional series resistances that are added to R_{S+} and R_{S-} . (**Figure 1**). A large imbalance between the contact resistance of the two leads will produce a large common-mode signal, just as if there was a large imbalance between R_{S+} and R_{S-} .

If it is impossible to eliminate or properly balance the contact resistance of the excitation leads, you can reduce the common-mode voltage at the sample by inserting a balancing resistor in series with one side of the drive current path. **Figure 2** shows a 15-pin D-shell breakout connector on the rear panel of the AC Transport controller where an appropriate balancing resistor may be installed.

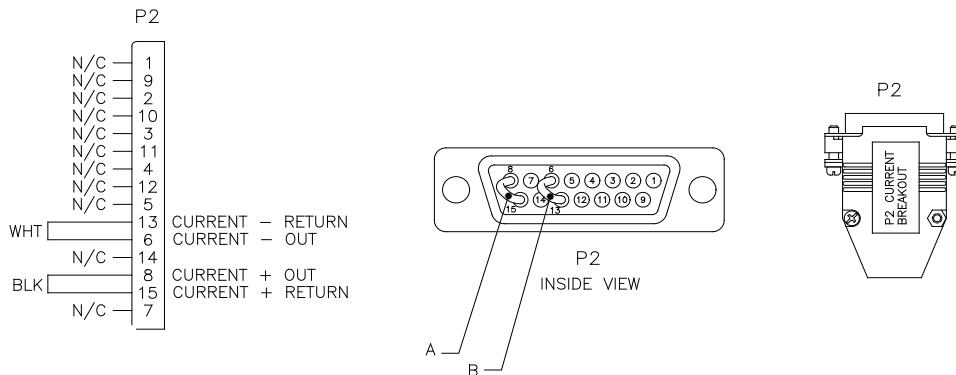


Figure 2. Circuit and actual diagram of the 15-pin D-shell breakout connector provided on the rear of the AC Transport controller. Balance resistors can replace either jumper “A” or “B” to balance out any common-mode voltage.

It is not necessarily a good idea to simply increase the overall resistance of the circuit. As the total resistance of the excitation circuit increases, the relative stability of the individual resistive elements becomes more stringent. In other words, if the resistance of the drive circuit is large, even a very small percentage of imbalance in the total circuit resistance can produce a common-mode signal, which is large compared to the voltage across the sample.

Minimizing (V_a+V_b) By Reducing the Drive Compliance

Another way to reduce common-mode effects is to simply reduce the compliance voltage seen at the voltage sources shown in the drive circuit. This can be done with the AC Transport option by selecting the **Optimize for Low Resistance** measurement parameter. This will reduce the

compliance voltage in the excitation circuit by a factor of 10 while maintaining the same drive current. Selecting the next smallest resistance in the drive circuit as shown in **Table 1** does this.

Estimating the Effects of Common-Mode Leakage

An example may be useful here to demonstrate quantitatively the degree of common-mode leakage that might exist in a measurement. The amount of leakage due to a resistance mismatch can be calculated as follows:

$$V_{\text{Leakthrough}} = \frac{V_{\text{Source}}MG}{\text{CMRR}}$$

Here, $V_{\text{Leakthrough}}$ is the artifact voltage that will erroneously appear to be at the sample because of common-mode leakage. V_{Source} is the driver compliance voltage, M is the overall percentage of resistance imbalance, G is the preamplifier gain, and CMRR is the common-mode rejection ratio of the preamplifier.

Assume that a sample was prepared with bonding resistance in the excitation leads of 9.0 and 10.0 ohms. Assume that we wish to excite the sample with 10.0 mA of current. For these parameters, the AC Transport option will select the 20mA drive range for which R_{S+} and R_{S-} are 50 ohms. Assuming the two 50 ohm resistors are perfectly matched, the imbalance, M , is computed as $((10.0-9.0)/2) / (50+10) = .0083 = 0.83\%$.

If the sample resistance is negligible compared to the drive and contact resistance, then the compliance voltage, V_{Source} , will be $(50\Omega + 10\Omega)10.0\text{mA} = 0.6$ Volts. If the measurement is made with the 1000x preamplifier, which has a CMRR of about 120dB, then the common-mode leakage voltage will be given by:

$$\frac{(0.6)(0.0083)(1000)}{10^6} = 5\mu\text{V}$$

At a gain of 1000, this corresponds to 5 nV at the sample. If the sample is driven with an excitation of 10 mA then the common-mode leakage will create a measurement artifact of $(5\text{nV})/(10\text{mA}) = 0.5$ uOhm.

It may be extremely difficult to actually measure the contact resistance between the electrical leads and the sample itself. However, calculating the amount of common-mode leakage, one can expect using likely values of the contact resistance can help determine if additional steps are needed to reduce the resistive imbalance. Such calculations may also provide a general estimate of the importance of the common-mode signal, helping to distinguish common-mode leakage effects from the true voltage across the sample.

Conclusion

Various instrument characteristics such as the effective drive balance, common-mode rejection ratio of the amplifiers, and the voltage compliance of the excitation circuit all affect common-mode leakage. In addition, sample characteristics such as imbalance in the contact resistance and the resistance of the sample itself can also affect the amount of common-mode leakage in any given measurement.

Properly balancing all elements of the excitation circuit and reducing and/or balancing the contact resistance to the sample will minimize the effect of common-mode leakage. While false voltages produced by common-mode leakage can be hard to distinguish from the true sample voltage, calculating the amount of common-mode signal expected in a given measurement will alert the cautious experimentalist to be aware of the potential problem.