Quantum Design

APPLICATION NOTE 1584-202

Inductive Cross-Talk during Alternating Current Measurements: Guidelines for Sensitive Measurements

by Craig Bauer, Quantum Design Staff Engineer

Inductive cross-talk (ICT) is an effect inherent to all instruments that utilize alternating current. Along with capacitive and self-inductive effects, it is one of an instrument's reactive (that is, nonresistive) properties that concerns designers of sensitive measurement devices. Researchers who utilize sensitive instrumentation, however, may be likely to overlook these effects, which manifest themselves relatively rarely. For the careful scientist, though, understanding ICT and how to deal with it can be critical to achieving the cleanest possible data, especially during extremely sensitive measurements. This document is intended to help researchers understand and effectively eliminate inductive cross-talk from sensitive measurements.

Inductive cross-talk is voltage noise resulting from the mutual inductance of closed circuits with paths located near one another. That is, the changing magnetic field created by an alternating current in one circuit induces spurious signals in a neighboring circuit according to Faraday's law, $V = -d\Phi/dt$. The offending circuits may be of almost any type, but the most obvious and instructive to discuss are the drive and detection circuits of a system designed to excite an unknown sample and measure its response to that excitation—electrically, magnetically, thermally, and so on. **Figure 1a** illustrates how ICT arises in an electrotransport measurement such as four-wire resistivity. **Figure 1b** illustrates ICT in an inductively coupled measurement such as AC susceptibility. In such cases, ICT may make up a significant fraction of the signal in the detection circuit whenever the sample response is very small, because the experimentalist frequently uses sizeable excitations to achieve a measurable response from the sample, thereby inductively exciting the entire detection circuit along with the sample itself. So whenever the sample response is very small, the researcher may need to closely watch the raw signal being measured and should be alert to the presence of reactive signal components, such as inductive cross-talk, that are not caused by the sample.

Careful instrument designers minimize ICT with geometric considerations and shielding, but any conductors external to the instrument itself, such as cabling and sample leads, are also subject to ICT. This document primarily addresses these and similar aspects of a measurement over which the instrument operator has control. It will be assumed that a sinusoidal AC signal is the cause of ICT, because this covers the vast majority of cases, but ICT can also arise from square wave, saw tooth, and other forms of alternating excitations.

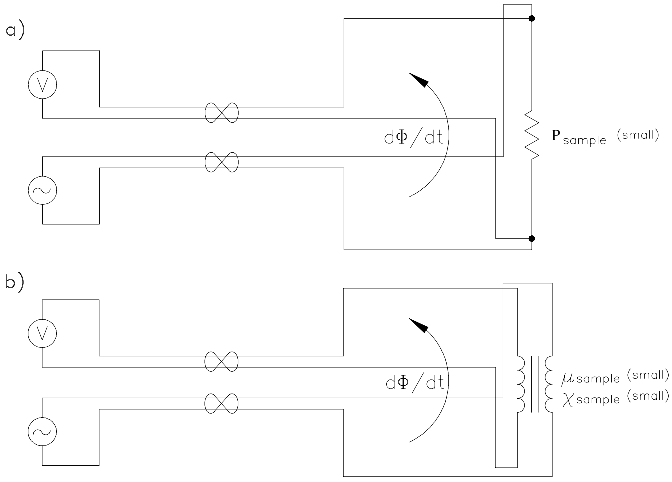

Figure 1. Generalized schematic of inductive cross-talk in (a) a four-wire resistivity measurement and (b) an AC susceptibility measurement. The loop area where the lead twisting lapses is greatly exaggerated. Inductive cross-talk can have similar effects on other types of measurements, although, depending on the measurement type, the manifestations may vary.

Linear ICT

In its most fundamental and common form, ICT is a linear effect with the offending excitation because $d\Phi/dt$ α dI/dt. That is, the flux through the receiving circuit is usually proportional to the current through the exciting circuit. In this case ICT has easily predictable properties. When caused by a sine wave excitation, ICT manifests itself as a sine wave 90° out of phase with the exciting signal. Therefore, in transport measurements, synchronous detection using a lock-in style amplifier should help eliminate ICT to a large extent. The Quantum Design AC Transport Measurement System (ACT) option for the PPMS is one example of an instrument that uses synchronous detection to filter out signals not caused by the sample itself.

To determine whether ICT is affecting a transport measurement, such as a resistivity or Hall coefficient measurement, changing the excitation frequency is a quick and powerful method. Since these transport properties do not depend on excitation frequency in nonreactive samples (most cases), *any* frequency dependence of the measured response signal must be due to reactive elements of the measurement circuit and not to the sample itself. If a synchronous detection transport measurement instrument reports a frequency dependence in its readings, either its synchronous detection may not be working properly or its reactive elements may not be producing a signal with a 90° phase shift, and the researcher may need to concern himself with nonlinear ICT (see below.)

It is also possible for the sample itself to be reactive or for the measurement *method* to be reactive in nature. (AC magnetic moment measurements, for example, are often performed inductively.) In these cases synchronous detection does not help identify ICT because the sample response may have an unknown phase relative to the driving signal. Furthermore, the sample response may also show frequency dependence, so ICT must be treated in the most direct manner possible. The signal caused by ICT can be measured in absence of a sample and then used as a base-line reading to subtract from subsequent data. Notice that a vector subtraction is required, because the base-line signal has both amplitude and phase that must be considered relative to the signal of interest. Quantum Design's inductively coupled AC susceptometer, the ACMS option for the PPMS, actually does this. One step in the ACMS AC susceptibility measurement process is to place the sample in a magnetically "invisible" location relative to the pickup coils and then measure the response from the pickup coils when excited without a sample visible. This is done every time a measurement is performed in order to account for variations in the system's reactive components with changes in temperature, magnetic field, and excitation amplitude. This method works well to account for ICT and other reactive elements of the device and is generally more effective than using calibration tables or formulas. The same concept can be applied to transport measurements. If ICT is affecting a transport measurement, a set of base-line readings for subtraction from the sample data can be obtained by measuring a perfect four-point short. (Consider **figure 1a** with $R_{sample} = 0$.) Note, however, that the Quantum Design AC Transport does not report the phase of the measured signal. This information can be estimated by examining the measured signal using the BNC output on the front of the Model 7100 AC Transport Controller.

To see the magnitude of ICT that you might reasonably expect from a pair of circuits, consider the fixed arrangement of wires in **figure 2**. One wire carries an alternating current of amplitude I and frequency ϖ, while the other two wires, situated parallel to the first at a distance r_1 and r_2 away, are part of a neighboring circuit, and their separation ($r_2 - r_1$) continues for length l.

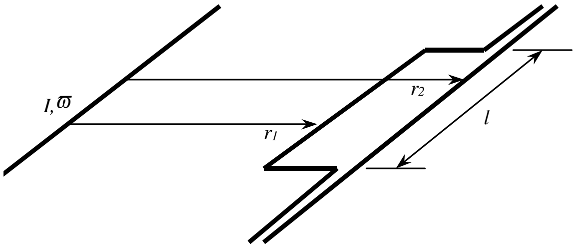

Figure 2. Example Arrangement of Cross-Talking Circuits

The flux through the area of the circuit shown can then be calculated from Ampere's law:

$$(1) \qquad \Phi(t) = \int_{r_1}^{r_2} l \frac{\mu_0 I \sin \varpi t}{2\pi r} dr = \frac{l\mu_0 I \sin \varpi t}{2\pi} \ln \frac{r_2}{r_1}$$

and the induced voltage in the circuit due to this changing flux, according to Faraday's law, is

(2) $$V = -\frac{d\Phi}{dt} = \frac{-l\mu_0 I\varpi \cos\varpi t}{2\pi}\ln\frac{r_2}{r_1}$$

For $l = 1$ m, $I = 25$ mA, $\varpi = 100$ Hz, $r_1 = 1.00$ cm, and $r_2 = 1.05$ cm, the magnitude of V is 24 nV. For a sensitive device, this level of voltage may be detectable. If the current in the neighboring wire is increased to 250 mA and the frequency increased to 1 kHz, the induced voltage becomes 2.4 µV, which will affect a low-level measurement in many instruments if not filtered out or otherwise carefully accounted for.

Nonlinear ICT

Simple, linear ICT is usually easy to identify and address. Guidelines for dealing with ICT are given in the next section. A more mysterious-looking situation may arise when the magnetic flux through a circuit is altered by a material in or near the circuits so that the flux through the receiving circuit is no longer directly proportional to the current through the exciting circuit, but is also related to the magnetic properties of the intervening material. Such a material may act a bit like an inductor core. This can be an especially salient point for measurement circuits that encounter a great variety of materials along their paths or circuits that pass into a region of highly variable material properties, such as inside a variable temperature cryostat. This situation exists, for example, in zero magnetic field for specific temperatures of the PPMS sample chamber electrical feedthrough, where the lead twisting lapses to pass the electrical signals into the hermetically sealed sample chamber of the cryostat. (For more information, see Quantum Design service note 1078-301.)

If the wires in **figure 2** were near a slab of material with permeability μ, the voltage induced in the circuit could be changed by a factor of up to μ/μ_0, depending on the proximity of the slab and its geometry relative to the wires. A high permeability means that the material acts to amplify the magnetic flux caused by the exciting circuit, Φ, and thus increases the $d\Phi/dt$ that causes ICT. Likewise, a very low permeability material could fortuitously attenuate the flux through the pickup circuit. Furthermore, if the material creates significant losses (due to hysteretic behavior, for example) or is being excited over a nonlinear portion of its M vs. H curve (due to saturation, for example), the resultant measured signal can be quite abnormal and may not look at all like a smooth sine wave. This can be observed by noting the shape of the signal in the time domain or in phase space, or by noting the level of harmonic contribution to the raw signal, which is reported by many digital instruments, including the Quantum Design AC Transport and ACMS. With inductively coupled instruments, harmonic contribution can be related to the sample, but for most voltage-sensing measurements, such as electrotransport measurements, significant harmonic contribution indicates either poor raw signal quality or a reactive sample. Remember that a harmonic contribution of –20 dB represents 10% of the signal, and in most AC measurement schemes the detected signal is expected to be entirely at the fundamental frequency. If abnormal wave forms are observed, a zero-sample measurement should be performed to verify that the effect is not sample related, as noted above.

Finally, notice the assumption in equation 2 that r_1 and r_2 are fixed. If r_1 and r_2 vary with time—that is, if the wires are moving for mechanical or electromagnetic reasons—equation 2 must be changed to account for this, and ICT no longer follows simple sine wave behavior. With moving conductors, signals can be induced in a circuit even when no alternating currents are near by. It is generally good practice to ensure that leads do not move to avoid this type of behavior.

Guidelines for Dealing with ICT

Several simple guidelines can help greatly reduce ICT below detectable levels. Most are common sense for researchers performing sensitive measure-ments, but are collected here as a reminder of conscientious measurement techniques. The first is to keep the $d\Phi/dt$ caused by the exciting circuit small by keeping the exciting frequency at moderate to low levels whenever practical. ICT is a purely inductive effect and vanishes at low frequencies, as indicated by equation 2. The main reason for using AC measurement techniques is usually to allow a lock-in style measurement, which does not require kilohertz measurement cycles. Just as you would not perform delicate surgery in the back of a moving ambulance, you should not expect to measure meaningful small signals when the measurement circuit is being driven at rapid frequencies. Extremely sensitive measurements of voltage should be carried out at moderate to low frequencies to avoid inductive cross-talk.

The example in **figure 2** shows a very specific geometric arrangement of wires. ICT can also be eliminated very effectively by manipulating the geometry of the cross-talking circuits such that flux no longer couples into the detection circuit well. This can be achieved by twisting together the leads of each circuit, or by using coaxial leads. In regions where it is not possible or practical to do this—for example, at electrical connectors and feedthroughs —equation 2 indicates three dimensional considerations that help minimize ICT. The first is to reduce l, reducing the length of sample leads subject to ICT. The longer the circuit is, the more chance it has to pick up cross-talk. This applies as a general rule of thumb: Do not make leads any longer than necessary when performing sensitive measurements. When dealing with a specific lapse in lead twisting or shielding for the purposes of an electrical connector, the length of unprotected conductor should likewise be minimized. The second dimensional consideration is to reduce the ratio r_2/r_1 by reducing r_2 relative to r_1. This means physically bringing the conductors of the pickup circuit as close together as possible to minimize its loop area. Finally, the ratio r_2/r_1 can also be reduced by increasing r_1; that is, by increasing the total distance between the cross-talking circuits. Altering the geometry of the conductors in the pickup circuit relative to the exciting circuit such that equation 1 no longer applies also drastically reduces ICT. This could be achieved, for example, by rotating the plane that contains the pickup circuit conductors in **figure 2** 90° about an axis between the circuit conductors and parallel to them.

Because ICT generally becomes a factor only when measuring very small signals, another way to address the issue is to increase the size of the signal being studied relative to the signal arising from ICT. Depending on the measurement type, this may be achieved by using a more massive sample, by changing the geometry of the sample or the geometry of the contact separation, or by changing other measurement conditions. Notice that increasing the drive amplitude not only increases the signal from the sample, but it also increases the amplitude of the $d\Phi/dt$ that causes ICT and is therefore not always a useful method of fighting inductive cross-talk. Increasing the drive amplitude can be effective if cross-talk is mediated by a saturating paramagnetic or ferromagnetic material, so increasing the drive increases the sample signal significantly more than it increases $d\Phi/dt$. But in the case of nonlinear ICT, it may prove useful to first eliminate the factors that cause the effect to appear nonlinear, by fixing all sample leads and by removing high permeability materials in close proximity to the pickup circuit whenever possible.

Conclusion

Inductive cross-talk in AC measurements is a fairly simple problem to diagnose and treat. Signals 90° out of phase with the exciting signal are indicative of inductive coupling, and so are signals with a frequency-dependent amplitude. When material properties near cross-talking circuits significantly alter the magnetic flux or when cross-talking circuit elements are moving, a signal due to ICT may not be 90° out of phase with its exciting signal and may not even appear as a simple sine wave. To verify that ICT is the dominating effect during low-level measurements, an instrument should be made to take a reading in a manner that is known to produce no external signals (that is, no sample). If there is indeed a signal produced in this manner, it is internal to the instrument or its cabling and can be treated directly or subtracted from further readings. To treat ICT directly, consider lock-in measurement tech-niques, lead twisting, lead separation, lead geometry, and lowering the frequency of the exciting signal.
It may also prove very useful to increase the signal of interest by measuring a more massive sample, by maximizing contact separation, by altering sample or sample contact geometry, or by other means.
When nonlinear ICT appears, eliminating the cause of the nonlinearity may sufficiently reduce the overall level of ICT so that lock-in measurement techniques can be used successfully. Following these guidelines should yield the conscientious researcher inductive cross-talk sufficiently low to utilize today's most sensitive instruments to their full potential.