

Application Note Magnetoelectric Response Task Rev C

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Introduction

An exciting new area of scientific exploration examines the potential usefulness where magnetic field effects occur simultaneously with ferroelectric effects in materials and structures. Where these two properties, ferromagnetism and ferroelectricity, are coupled in the same material, the material is called a *multiferroic*. The most common material studied today for this characteristic is Bismuth Iron Oxide (BFO). Similar properties can be created in a device by physically bonding magnetic materials to piezoelectric or ferroelectric materials. Such a device will be referred to in this application note as a magnetoelectric composite device. Magnetoelectric composites have great potential to create new sensors and energy harvesters. One such device was fabricated at Radiant using an RC-166A Sensor Die (http://www.ferrodevices.com/1/297/sensor_die.asp) by gluing a magnet to the capacitor surface. This device was used to conduct the example magnetoelectric response test described later in this application note.

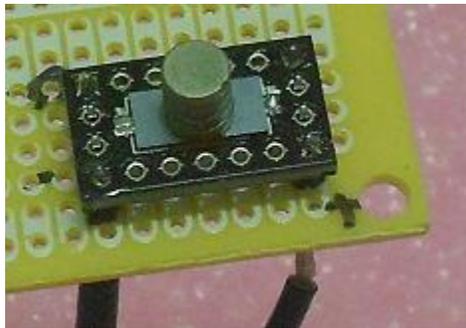


Fig. 1: Hand-built magnetoelectric sensor

The magnetoelectric test is executed in Vision on a Precision ferroelectric tester by the Magnetoelectric Response Task. For brevity, the task will be referred to in this document as the MR Task. For those unfamiliar with the Vision operating system on Radiant testers, please go to <http://www.ferrodevices.com/1/297/software.asp> and select the *Introduction to Vision*.

There are a variety of tests that may be executed on a multiferroic capacitor or an ME composite.

- 1) Cycle a magnetic field around the sample while measuring any charge generated by the sample.
- 2) Execute polarization hysteresis loops within fixed magnetic fields to compare the loops taken at different magnetic field levels.
- 3) Execute a polarization hysteresis loop and measure the magnetic field generated by the sample.

This application note will deal only with test #1.

Organization of this Application Note

For those researchers with primary experience testing capacitor polarization, the magnetic measurements below will seem overly complex. The reason is that a capacitor is a self-contained two terminal device where the geometry of the electric field is permanently defined by the geometry of the electrodes. The two terminals need only be attached to the DRIVE and RETURN terminals of the Precision tester to acquire good measurements. For the magnetic measurements described below, the sample will be stimulated by a magnetic field through open air. This opens the measurement to additional sources of noise and error over that of a polarization vs voltage measurement. In particular, EMF sources that would not affect a capacitor easily stimulate the antenna created by the magnetic coil used in the test fixture. As well, the geometry and physical mounting of the sample in a magnetoelectric response test can have a dramatic effect on the measured response. Consequently, great effort is made in this application note to point out possible sources of error or noise in a magnetoelectric response measurement, making the procedures appear to be complex and difficult. As well, there are two independent scientific communities working on this subject: 1) ferroelectricians that are familiar with electrical characterization of materials but are not familiar with magnetic measurements and 2) physicists familiar with magnetic fields but unfamiliar with the complexities of remanent polarization. For this reason, the application note provides explanations for theory and testing from the point of view of either community. The explanations may seem simplistic to one of the groups but will be new information for the other.

The Precision test equipment have charge measurement accuracies better than 0.5% for each measurement. Deviations of measured values from the sample's true values will most likely arise from fixturing or a host of possible external error sources, many of which are noted in this application note. Dr. Chee-sung Park of Virginia Tech has executed measurements of a known sample using the traditional voltage sensing technique with a lock-in amplifier and compared those results to the same charge-based measurement technique described in this application note. He found an excellent correlation between the two tests. His paper is published in *Smart Materials and Structures*. [Park, Priya, and Evans, *Smart Mater. Struct.* 20 (2001) 082001 6pp].

At the end of this application note there is an example experiment measuring the response of the sample in Figure 1. The experiment was not intended to meet strict academic guidelines for publication. The theoretical discussion that follows builds the foundation for testing this composite device built from off-the-shelf materials. The experiment was organized to provide a framework for highlighting how such a measurement is executed, emphasizing the greater complexity of magnetic testing over ferroelectric testing, and identifying possible error sources that might affect the accuracy of the results. Despite these limitations, the measurement was still within 15% of the prediction for an ideal sample. The accuracy and reproducibility of the equipment and test procedure Radiant provides will be investigated independently by the research community as time progresses.

If you have any corrections to suggest for the application note, improvements to the test procedures, or additional material that should be discussed, please contact us at radiant@ferrodevices.com or 505-842-8007. I am by upbringing a ferroelectrician so I especially welcome corrections to this document from the magnetics community.

Anatomy of a Magnetolectric Response Test

In a normal polarization vs voltage test, the DRIVE output of a Precision tester stimulates the capacitor sample with a voltage waveform while counting electrons coming out of the sample into the RETURN input. The Magnetolectric Response Task in the Vision Library drives a magnetic coil with the tester DRIVE output while capturing any charge transfer into or out of the sample. It is the symmetrical parallel to the polarization hysteresis test with the exception that the sample is stimulated by a magnetic field waveform instead of an electric field waveform. The simplest test configuration for this test is in Figure 2.

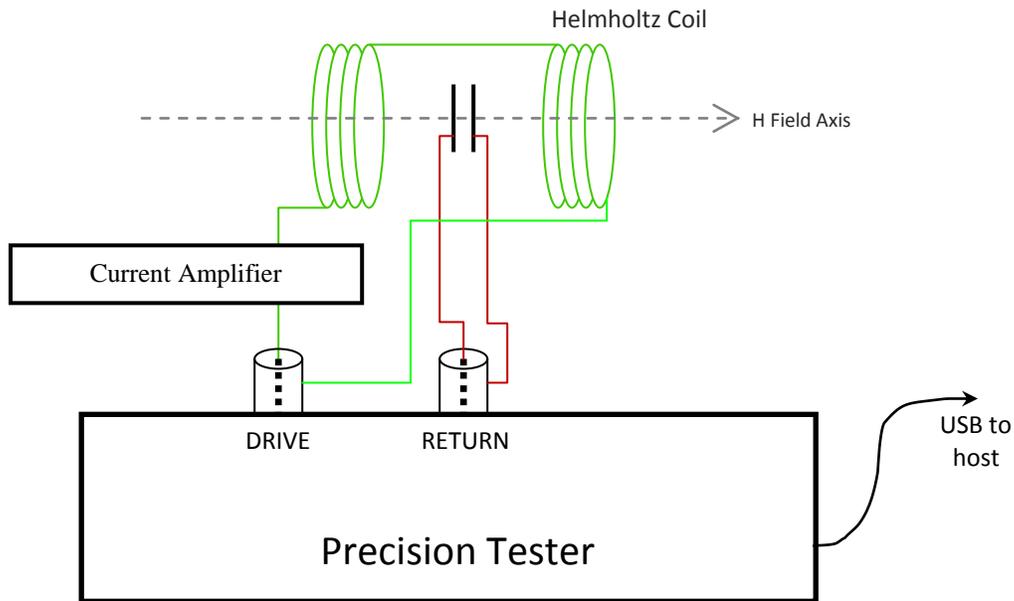


Fig. 2: The most basic test configuration for the MR Task

In the configuration of Figure 2, the sample sits at the center point of a Helmholtz coil. A Helmholtz coil is not necessary. A single magnetic coil or some other type of voltage-or-current-driven magnetic field generator will do. For the rest of this application note, the coil used to generate the varying magnetic field will be denoted as the “driver coil”.

The test can be conducted without the current amplifier using the current generating circuits of the DRIVE output directly. Note however that the Radiant testers are capable of generating only 30mA to 200mA depending upon the tester type. Most magnetic coils require several amps in order to generate a magnetic field of sufficient amplitude to stimulate a measureable response in a multiferroic material or an ME composite. Kepco, for one, offers several suitable current amplifiers for this purpose, including the BOP36-6 (36V, 6 amps) or the BOP50-8 (50V, 8 amps). Magnetic coils and associated amplifiers exist that will generate a Tesla or more of magnetic field. If a choice is possible, select a current amplifier with the lowest voltage output at the maximum allowed coil current to reduce the amplifier power specifications.

The sample in the test circuit of Figure 2 is grounded on one side and connected to the RETURN input on the other. Since the RETURN input is a virtual ground, the sample will have zero volts across it during the entire test, preventing the generation of a back voltage across the capacitor that might interfere with the magnetically-induced charge generation. It is possible to apply a DC bias across the sample during the test execution. That configuration will be discussed later in this document.

The charge generation measured during the test execution must be plotted against the B-field generated during the test. There is no magnetic field sensor shown in Figure 2. Therefore, the magnetic field for tests using the configuration in Figure 2 must be estimated from the voltage produced by the DRIVE output into the current amplifier. This requires knowledge of the voltage-to-current conversion ratio of the current amplifier as well as the current-to-magnetic-field conversion ratio of the driven coil(s). These two values are multiplied together to provide the Voltage-to-Gauss conversion factor needed by the MR Task to determine how much voltage must be used to generate the requested magnetic field.

Two other methods of determining the magnetic field during the test are shown in the two figures below. The MR Task supports all three techniques. Note that Sensor 1 is defined for current sensing only while Sensor 2 is defined for field sensing only.

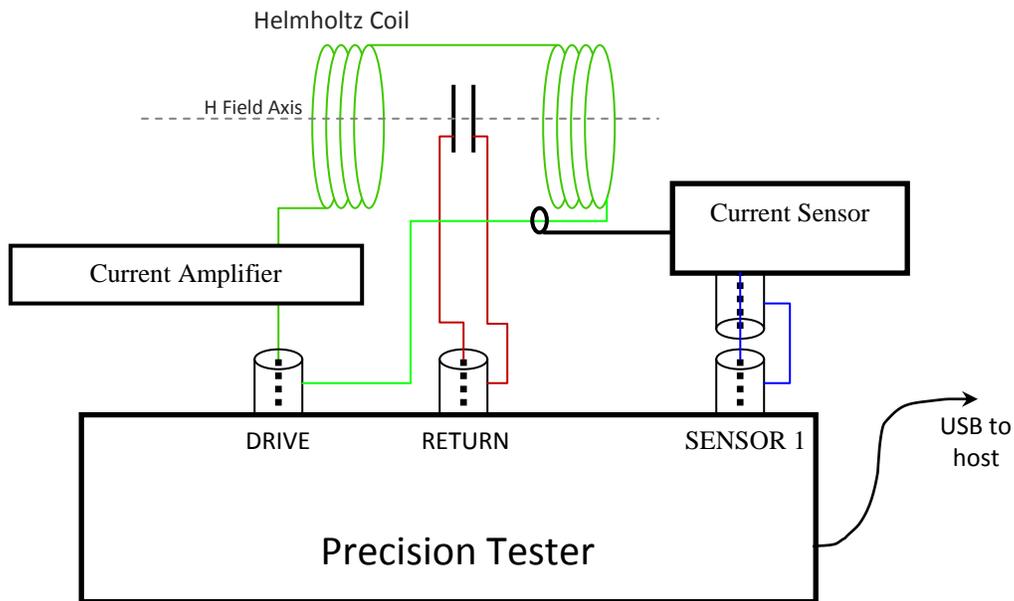


Fig. 3: Sensing current on Sensor 1 to determine magnetic field.

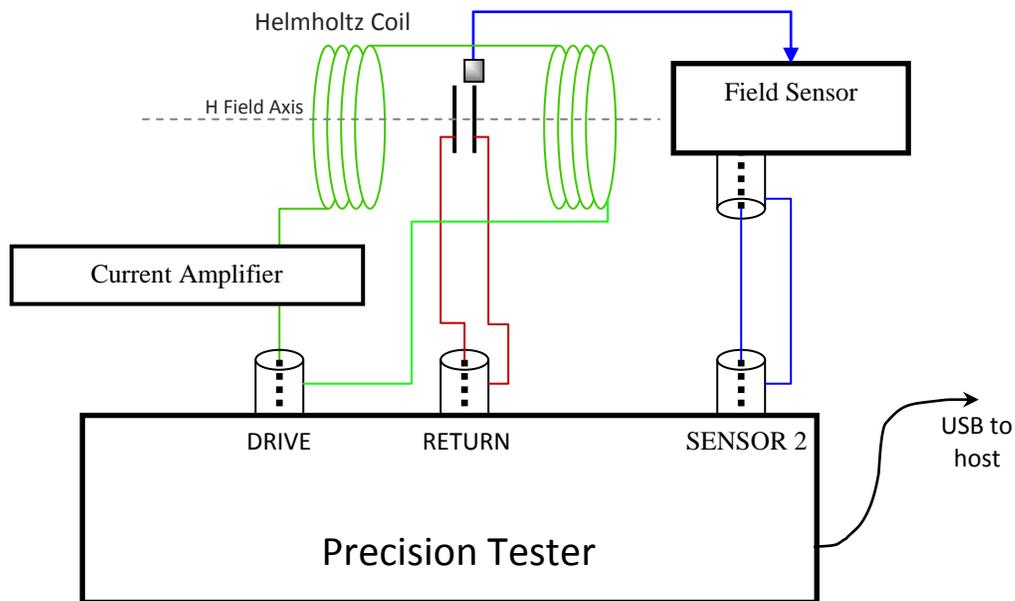


Fig. 4: Sensing magnetic field directly on Sensor 2.

Magnetic Field Sensors

There are several types of magnetic field sensors. The two types generally available from manufacturers are flux meters and Hall Effect sensors. Flux meters use a *search coil* placed in the magnetic field at the location of interest. The magnetic flux through the cross-section of the coil is measured by the meter. Flux meters of sufficient speed and sensitivity are available but, due to the use of a search coil as the sensor, they measure the flux over an area that may be larger than the sample. There must also be enough room in the test volume of the magnetic driver coil to fit the sample and the search coil.

Hall Effect sensors have a small sensing area and are also fast enough to keep up with the MR Task stimulus waveform. Hall sensors are read by Gauss meters.

For both types of sensors, the meter must have a voltage output that is proportional to the sensed magnetic field. This output is connected to the Sensor 2 BNC input of the tester. A coefficient must be entered into the MR Task setup menu telling Vision the conversion ratio to multiply times the voltage output of the meter to arrive at the sensed B field strength. Both SENSOR inputs are measured synchronously and simultaneously with the DRIVE output and the RETURN input to ensure that there is no time skew between the measured signals.

The frequency response of the meter is very important in order to prevent distortion of the results. Even if a flux or Gauss meter is accurate, it will distort the plot of charge vs magnetic field if the voltage output of the meter lags behind the test. We recommend executing the MR Task measurements no faster than 10Hz and no slower than 1 Hz. Depending upon the tester type, the test will capture 500 or 1000 data points

evenly spaced in time during the stimulus waveform, making the maximum sample frequency 10 kHz. If a meter is used to measure the magnetic field during a test, it must be as fast as or faster than 10 kHz. It must also be stable down to 1Hz, the slowest test frequency. Most meters operate in both DC mode and AC mode. AC is the preferred mode for operation but the user must be careful to ensure that the meter and sensor will be both fast enough *and* slow enough. Some meters in AC mode cut off at frequencies faster than 1 Hz.

NOTE: Consistent with standard electrical engineering filter theory, many meters and amplifiers specify their frequency limits as the point where a 3-decibel drop (50%) occurs in the output signal relative to the input signal. This is not an acceptable frequency limit definition to use with a Precision tester since the measurements made by the tester are *absolute measurements*. In this document, a 10 kHz or 1 Hz frequency limit for a magnetic field sensor means that *the meter reports a value for the measured field that is essentially 100% of the true value of the field independent of frequency*. If a meter suffers a drop in the reported signal amplitude at the maximum test frequency, that drop will decrease as the test is slowed down, meaning that the tester, which reports the *absolute* value of signal it measures on the SENSOR input, will not correctly plot the results of the MR Task measurement. The true frequency response of a meter can only be determined by testing the meter over the desired frequency range, not by depending upon the stated meter specifications. If possible, use a meter with a frequency response at least 10 times faster and preferably 100 times faster than the fastest intended sample rate during a test. Where necessary, select a test frequency slow enough to give the maximum frequency margin for the field meter being used.

Additional Test Parameters

Radiant has an accessory compatible with its Multiferroic, Premier II, RT66B, and late model LC testers that allows Vision to apply DC voltages during tests. The accessory is called the I²C DAC Controller.



Fig. 5: I²C DAC.

The I²C DAC Controller connects to the I²C port of the tester using 6-wire telephone cable that may be acquired from Radiant. The cable transfers computer commands and $\pm 15V$ power to the unit. There are two standard tasks in Vision that control the I²C DAC Controller as a voltage source. One, the I²C Relay Task, opens and closes the output relay of the unit. This relay can be used to isolate the I²C DAC Controller output from the instrument or device it is controlling. The second task, the I²C Volts Task, assigns a voltage to the I²C DAC Controller output. The assigned voltage for the I²C Volts task can be incremented inside a test loop. More information about the I²C DAC Controller may be found in the document “Application Note – I²C DAC.pdf”.

The I2C DAC Controller allows greater complexity in magnetoelectric testing. The drive coil and sample may be placed inside the active volume of a larger field coil. The magnetic field generated by the field coil can be used to set a background static magnetic field level to bias the sample. The voltage output of the I2C DAC Controller is used to set the value of this background magnetic field.

There is a task to control a magnetic field coil using the I2C DAC Controller. The task is called the DC Magnetic Field Task. It accepts the voltage-to-field coefficients mentioned earlier so the DC field can be defined in terms of H field. The value of the H field can be incremented or scaled inside a loop like other test parameters in Vision.

The MR Task itself also controls the I2C DAC Controller. This allows the user to set up a series of MR measurements inside a Branch Loop with fixed MR test parameters while incrementing the DC bias field across the sample on each loop. In a single test execution, the user can capture the MR response of the sample as a function of increasing bias field and plot all results. A diagram of the MR test with field coil is in Figure 6.

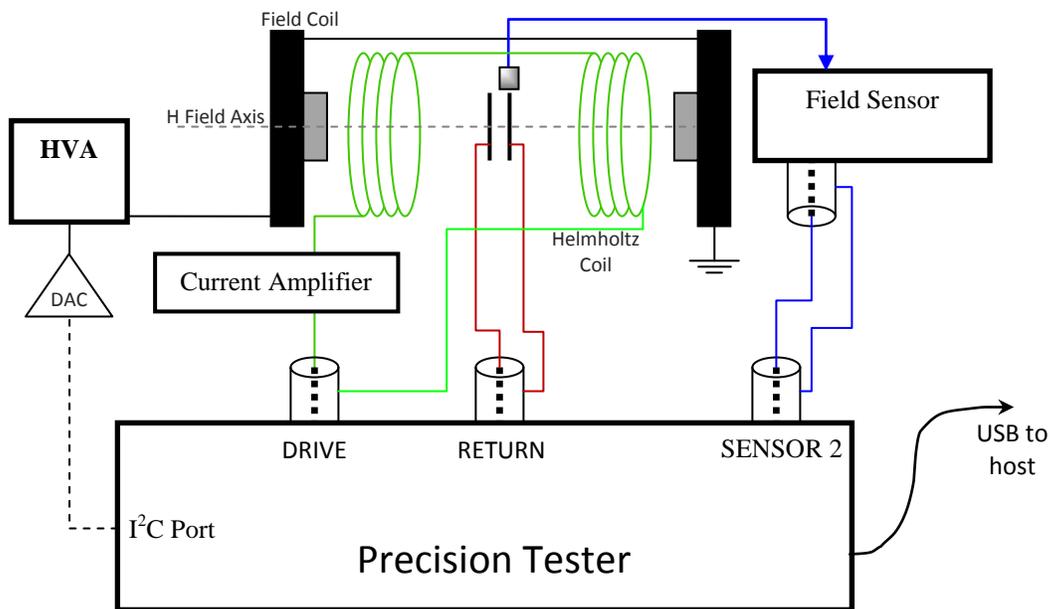


Fig. 6: Measuring with a bias magnetic field.

A second application for the I2C DAC Controller is to apply a DC voltage bias to the test capacitor during the test. The I2C DAC Controller may be set to one of eight addresses and more than one I2C DAC Controller may be driven by a tester as long as each controller has a different address. A window specifying the address for each I2C DAC Controller appears in the menu. The physical address for each DAC is set by jumpers inside the I2C DAC Controller enclosure.

The final test configuration, including the field coil and sample voltage bias, is shown in Figure 7.

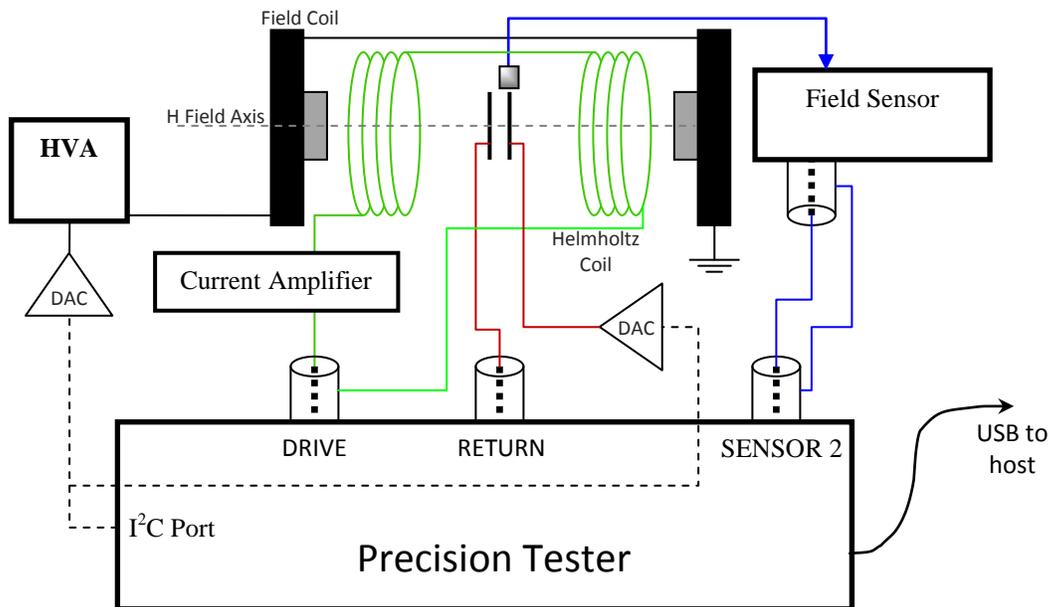


Fig. 7: The MR test configuration with DC field coil and sample voltage bias.

Note that in Figures 6 and 7 the magnetic axis of the field coil is aligned with that of the Helmholtz coil. This is a convenient arrangement but co-linear alignment is not required. In fact, the sample may generate its greatest response when all three axes of the sample, the Helmholtz coil, and the field coil are *not* aligned.

Magnetic Fields

Although the equations describing magnetic fields and the forces they generate look similar to the equations describing electric fields, they have a significantly different meaning. A “magnetic field” derives from changes in the *apparent* geometry of electric fields because the relative motion between charged particles causes length contraction as defined by Einstein’s Theory of Special Relativity (1905) and Dirac’s relativistic equation of motion (1928). While electric fields exist statically and are always present with the presence of charged particles, magnetic field effects require current, i.e. motion of charges, or changes in current, i.e. acceleration of charges. To account for the change in geometry, a new force vector must be added to the existing electrostatic force vectors. That is the magnetic force vector. The amplitude and direction of the magnetic field at any point in space is found by summing *the relative motion of all nearby charges* communicating with that point in space. The equations of magnetism and the forces it generates simplify the bookkeeping that keeps track of these net sums.

The first order of bookkeeping is to define a ledger to record the motions of all of the charged particles. This is the H-field, the *generated* magnetic field. It is oriented by definition at a 90° angle to the motion of every moving particle. Its amplitude is defined by the number of moving charges and their relative velocities. In the simplified geometry defined by a wire, the number of moving charges and their velocities is incorporated in a single parameter: current.

$$\mathbf{H} \text{ (at radius } r) = \text{Current through wire} / \text{circumference at radius } r \text{ from wire} = \mathbf{I} / 2\pi r \quad \text{Eq(1)}$$

The amplitude of the H-field varies linearly with the number of charges, linearly with their velocity, and inversely with distance from the wire.

The second order of business is to create a method of converting the H-field, the bookkeeping ledger, into the amplitude and direction of forces applied to other moving or non-moving charges, the B-field. This is accomplished in two steps:

- 1) Convert the H-field to a B-field by multiplying by μ .

$$\mathbf{B} = \mu\mathbf{H} \quad \text{Eq(2)}$$

and

- 1) Apply Lorentz's Force Law:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad \text{Eq(3)}$$

It is important to note that the direction of the B-field is parallel to that of the H-field and that the direction of the force on the moving charge is orthogonal to the H-field. The orthogonality of the force is represented by the cross product in Equation 3. An examination of the geometry of the magnetic field produced by current in a wire indicates that the amplitude of the magnetic force it applies to a moving charged particle is proportional to the amplitude of the particle's component of motion \mathbf{v} collinear with the direction of the current generating the magnetic field. This meets the definition in the Special Theory of Relativity that length contraction occurs along the mutual axis of motion between two frames of reference.

The parameter μ in Equation 2 encompasses all possible materials and includes not only current but bound charge and changes in polarization in the material which cause charged particles to change their position within the material lattice. Fortunately for the tests that will be executed with the MR Task, the sample will be suspended in air so the magnetic permeability μ effectively reduces to the μ_0 of a vacuum where only free current effects create magnetic fields.

$$\mathbf{B}_{\text{air}} = \mu_0\mathbf{H}_{\text{air}} \quad \text{Eq(4)}$$

Magnetic Force

The two most likely devices to be tested with the MR task are:

- 1) A capacitor with a multiferroic material between the capacitor plates or
- 2) A magnetoelectric composite consisting of a piezoelectric material physically coupled to a magnetic material.

In the case of the multiferroic capacitor, the magnetic field couples directly to polarization:

$$\mathbf{P} = \alpha \mathbf{H} \quad \text{Eq(5)}$$

The multiferroic sample is placed within the region where the magnetic field generator will produce an H-field and the charge generated by the sample at each value of the magnetic field is captured. The slope of the plot is the magnetoelectric coefficient for that material for that geometry.

$$\mathbf{P}/\mathbf{H} = \alpha_{ijk} \quad \text{Eq(6)}$$

For a magnetoelectric composite, the magnetic field generates a force against the magnetized portion of the composite which in turn transfers the force to the piezoelectric material to generate charge. There are two force equations governing this interaction. When a B-field is applied parallel to the axis of a magnet, the force is determined by Equation 7.

$$\mathbf{F} = \nabla[\mathbf{m} \cdot \mathbf{B}] \quad \text{Eq(7)}$$

Where

- ∇ = the derivative along the magnetic axis
- \mathbf{m} = the strength of the magnet
- \cdot = dot product of m against B

The dot product in Equation 7 measures the angle between the B-field vector and the magnet axis of magnetization. It reaches unity if the two vectors are *parallel* to each other. The dot product of m and B in Eq(14) will be zero if they are perpendicular to each other. \mathbf{m} will change in a magnetic field but for the purposes of this application note it will be assumed to be a constant during a test. Given these conditions, aligning the magnetic axis of the magnet with the B-field, Equation 7 reduces to

$$\mathbf{F} = \mathbf{m} * \delta\mathbf{B}/\delta x \quad [\textit{parallel B-fields}] \quad \text{Eq(8)}$$

Thus the force on a magnet will be determined by the *gradient* of B-field, not the absolute value of the B-field, in the region of the magnet.

The magnet will respond directly to the magnitude of the B-field if the B-field is applied *orthogonal* to the magnet so as to apply a *torque* to the magnet. The torque occurs because the B-field attracts one pole of the magnet but repels the other.

$$\boldsymbol{\tau} = \mathbf{m} * \mathbf{B} \quad [\textit{perpendicular B-fields}] \quad \text{Eq(9)}$$

For the magnetoelectric composite device, the force generated against the magnet times the associated piezoelectric constant will generate charge from the capacitor: $Q_i = d_i * F_i$ where “i” is the direction under observation. The charge equations for the magnetoelectric composite device thus become

$$Q_p = d_p * [\mathbf{m} * (\mu_0 \delta H / \delta x)] \quad [\textit{parallel B-fields}] \quad \text{Eq(10)}$$

$$Q_\tau = d_\tau * [\mathbf{m} * \mu_0 H / L_{\text{magnet}}] \quad [\textit{perpendicular B-fields}] \quad \text{Eq(11)}$$

Where

- d = the sample effective piezoelectric constant in the assigned direction.
- L_{magnet} = the length of the magnet against which the magnetic torque is applied.

Equation 10 calculates the charge generated when a vertical force generated on the piezoelectric capacitor is caused by the gradient of the driven magnetic field applied parallel to the magnetic axis of the magnet. The torque produced by a B-field in Equation 11 is divided by the length of the magnet, the lever arm, to

resolve the force applied at the magnetic pole perpendicular to the axis of the magnet. This force times the torque-based piezoelectric constant should predict the amount of charge generated by the sample in this geometry.

NOTE: The magnetic moment m and the B-field $\mu_0 H$ are not in bold face in the two equations because they have been reduced from vectors to a single directional amplitude. By reducing the geometry of the two conditions to parallel or perpendicular, the calculations may be executed as simple multiplications of amplitudes without need to resort to vector math. The reason for this approach is to simplify the experiment to be conducted at the end of the document. In reality, the Helmholtz coil will create a known linear axis for the B-field but m will more than likely have components in all three axes. As well, the amplitude and direction of m in the two equations is assumed to be constant during the experiment but those values will probably change non-linearly as a function of the applied B-field during the stimulus. Accurate characterization of these effects is necessary to determine the true coupling factors for the sample but that level of mathematics is beyond the scope of this application note.

The piezoelectric constants d_p and d_τ listed above are not the absolute material coefficients but the effective coefficients that take into account bending or twisting moments applied by the magnetic force to the piezoelectric capacitor and its substrate.

NOTE: Piezoelectric response is described using tensor mathematics with responses generated by forces along the three axes, torque around the three axes, and sheer along the three axes. As noted just above with the mathematics surrounding the magnetization vector m , the piezoelectric response is reduced to a single “equivalent” constant to simplify the mathematics for this application note.

Coils

The magnetic field generator most likely to be used with the MR task will be a magnetic coil. The straight wire of Equation 1 is bent into a circular loop to concentrate the H-field lines in the center of the loop. Multiple loops of the wire linearly increase the amplitude of the field. The central axis of the coil perpendicular to the plane of the coil is the axis of the H-field the coil generates. The value of the H-field of a coil as a function of the X position along the magnetic axis is given by Equation 12.

$$H = NIR^2 / 2(R^2 + x^2)^{3/2} \quad \text{Eq(12)}$$

Where

- R = radius of the loop
- x = distance from the center of the loop along the central axis.
- N = the number of loops

Equation 12 assumes infinitely thin wire occupying an infinitely small volume. In the real world the more loops of wire in the coil, the more volume the loop occupies. This effect spreads the distance from each loop if the coil to the sample, causing the true H-field to deviate from the theoretical field predicted by Equation 12. That is why field meters or Gauss meters employed during an MR Task execution provide the most accurate representation of the B-field compared to a field value calculated from the tester-generated stimulus voltage.

Equation 8 requires the value of the derivative of the magnetic field at the sample point. The derivative of Equation 12 is

$$\delta H / \delta x = (-3/2) N I R^2 [x / (R^2 + x^2)^{5/2}] \quad \text{Eq(13)}$$

The derivative of Equation 13 (not derived here) can be used to find the point from the center of the coil for the maximum gradient.

A Helmholtz coil consists of two identical coils coaxial on their magnetic axes separated linearly along that axis by a distance equal to the radius of the coils. The coils are connected so that current flows in the same direction through both coils. The advantage of the Helmholtz coil is that it can create a region of near-uniform magnetic field along the coil magnetic axes in the volume between the two coils. This area of uniform magnetic field can be calibrated quite accurately. If the separation of the two coils equals the coil radius and the magnetic field generated by both coils is calculated using Equation 12 for the point on the magnetic axis exactly equidistant between the two coils, the B-field at that point becomes

$$B = 0.716 \mu_0 N I / R. \quad \text{Eq(14)}$$

The field is reasonably uniform within a volume centered on that point. Proper selection of the geometry of the Helmholtz coil will ensure that the sample fits within that volume of uniformity.

The magnetic force generated by Equation 8 requires a gradient in the local magnetic field. The *gradient* of the magnetic field within the volume of uniformity of the Helmholtz coil is nearly zero by definition. A gradient may be achieved by placing the sample *outside* the central volume of the Helmholtz coil along the axis of the coils. Equation 13 can be resolved twice, once for each coil, and the results summed to determine the gradient of the magnetic field at the point of test. Equations 12 and 13 can also be used if only a single coil, not a Helmholtz coil, is used.

In summary, for samples that respond directly to the magnitude of the magnetic field using Equation 5 or Equation 9, a Helmholtz coil is best to use as the magnetic field driver since it will have a well characterized region of uniform magnetic field. If the sample depends upon the gradient of the magnetic field to generate a force, a Helmholtz coil has no particular advantage over a single coil.

Magnetic Moment *m*

Equations 8 and 9 contain the parameter *m*, which is the magnetic moment of the magnet embedded in the magnetoelectric composite.

$$m = \mathbf{M} * V \quad \text{Eq(15)}$$

Where

\mathbf{M} = magnetization of the magnet
 V = the volume of the magnet

Think of \mathbf{M} as being the magnetic equivalent of remanent polarization, a quantity *contained within a unit volume of the magnet upon which B fields act*. \mathbf{M} is the natural H field generated by the magnet and it is related to the B field in the following manner

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \quad \text{Eq(16)}$$

The H inside a magnet is not easily derived theoretically so for practical purposes, *m* should be measured as part of any experiment. For the purposes of this application note, we will use the ideal magnetic dipole equation to model *m* in the magnet of the reference sample.

$$\mathbf{B} = \mu_0/4\pi * 2m/r^3 \quad \text{Eq(17)}$$

$$2\pi\mathbf{B}r^3/\mu_0 = m \quad \text{Eq(18)}$$

Where
 r = 1/2 distance between magnet poles

Geometry Coefficient

The preceding discussion of magnetic field theory as it applies to the MR Task makes it clear that geometry plays a strong part in the conduct of the test. A magnetoelectric sample will have a magnetic axis unique to its sample geometry and construction. The orientation of that axis to the driven H-field during a test *as well as the location of the sample during the test* determine the actual force coupled into a magnetoelectric composite or the coupling of the H-field to the polarization of a multiferroic material.

Multiferroic materials and magnetoelectric composites that depend upon torque should be mounted in the central volume of uniformity of a Helmholtz coil. The MR Task need calculate the applied B-field using only the voltage-to-current coefficient and the current-to-B-field coefficient associated with the test equipment. However, if the sample is mounted so that its magnetic axis is at an angle to that of the driven B-field or a magnetoelectric composite that depends upon the gradient of the magnetic field is mounted away from center of the coil(s), a correction must be made to the B-field calculation. The MR Task has a third coefficient window for this purpose. This coefficient, the *Geometry Coefficient*, allows the user to add a geometry correction to the current driven into the driver coil by the tester. The user sets the voltage-to-current coefficient and the current-to-B-field coefficients to those values that will give the B-field at the center of the coil or the center of the Helmholtz coil. The geometry coefficient then allows adjustments to the applied B-field without having to change the other two coefficients.

NOTE: The user should always set the three coefficients to match the geometry of the test fixture and driver coil(s). The user should then input the value of the magnetic field *desired at the sample's location*. The MR Task will use the current amplifier coefficient, the driver coil coefficient, and the geometry coefficient to calculate the voltage required at the input of the current amplifier (See Figure 2.) to generate the requested B-field *at the sample*.

The equation for the output voltages from the tester to the test fixture is

$$V_n = \{\text{Requested B-field}\}_n / \{C_{\text{geometry}}\} / \{C_{B \rightarrow I}\} / \{C_{I \rightarrow V}\} \quad \text{Eq(19)}$$

Units of Magnetic Field

As noted in the previous section, the H-field sums all of the moving charges while the B-field determines the force. The two are related by the equation:

$$\mathbf{B} = \mu\mathbf{H} \quad \text{Eq(2)}$$

μ is the permeability constant mentioned earlier. It is broken up in to two parts: its value in a vacuum and its value inside a material.

$$\mu = \mu_0\mu_r \quad \text{Eq(20)}$$

μ_0 is the value in a vacuum and is equal to $4\pi \times 10^{-7}$. All of the MR Task measurements should be in air. The value of μ_r for air is 1.00000037, essentially 1.0. With little error, Equation 2 reduces to Equation 4.

$$\mathbf{B}_{\text{air}} = \mu_0 \mathbf{H}_{\text{air}} \quad \text{Eq(4)}$$

Inside ferromagnetic materials, like a magnet, the H-field is not constant but will change as a function of external magnetic fields. This means the μ changes as a function of external magnetic fields. This is the reason that the magnetoelectric response of a sample will change as a function of a DC magnetic bias field. μ_0 is always constant.

Both the H-field and the B-field have two independent sets of defined units. For each, one unit is defined by the fundamentals of physics. These are

<u>Field</u>	<u>Unit</u>
H	Amp/meter
B	Tesla

The H-field represents motion so its units make sense: the amp is the measure of how much charge is *flowing* through a wire and the distance is how far away from the wire lies the point of interest. The Tesla unit converts motion to force and is an honorific named for a guy who liked to build very big magnets, cause lightening shows, and compete with Thomas Edison. The Tesla in fundamental units combines force per unit charge with the units of velocity.

$$1\text{T} = 1 \text{ Newton per Coulomb} / \text{meter per second} = \text{Ns/Cm} \quad \text{Eq(21)}$$

The Newton per Coulomb is also the unit of electric Field E so Equation 21 can be rewritten.

$$1\text{T} = 1 \text{ Electric Field} / \text{Velocity} = \text{Vs/m}^2 \quad \text{Eq(22)}$$

The C/s term of Equation 21 allows the equation to be re-written to define a Tesla in terms of current.

$$1\text{T} = 1 \text{ Newton} / \text{Amp meter} = \text{N/Am} \quad \text{Eq(23)}$$

Remember that the H and B fields represent two entirely different things, motion (H) and force (B), so their units *are not related*. The permeability constant μ in Equation 2 converts one to the other.

The absolute values of the numbers that occur in magnetic equations involving H and B fields are unwieldy when using the primary units of Amp/meter and Tesla. So, the scientific community invented two other units.

<u>Field</u>	<u>Unit</u>
H	Oersted
B	Gauss

The Oersted is *larger* than the Amp/meter by the factor $1000/4\pi$ while the Gauss is smaller than the Tesla, $1/10,000^{\text{th}}$ of the Tesla. This arrangement makes sense if you plug these values into Equation 2 using only μ_0 . The result is that for any point in the H-field and the B-field, the *numerical value* of both of these units is the same even though they represent different concepts. In summary,

- 1) *one* Amp/meter does not convert to *one* Tesla using Eq(4) but
- 2) *one* Oersted does convert to *one* Gauss.

Do not forget that even though their scalar values are the same, the Oersted (H) sums charge motion while the Gauss (B) represents force.

Error Sources

The Precision testers make an absolute measure of charge: they count the number of electrons going into or out of the RETURN input synchronously with the stimulus waveform generated by the DRIVE output. Each Precision tester has enough sensitivity to measure the charge generated in a magnetoelectric sample by a magnetic field *without the need of a lock-in amplifier*. The key to increase the signal-to-noise of the measured response is to eliminate as much as possible the inclusion of charge created by test fixture parasitics or external noise sources.

Executing an absolute measurement, the RETURN input will count *every* electron independent of its source. Electrons do not have color so the ones from noise sources cannot be filtered out at the RETURN input. However, noise sources can be recognized by their signature in the measured response from the sample. The classic example is that of 60Hz noise arising from the fluorescent lights in the room. Each fluorescent bulb has an internal plasma which acts as a low impedance transmission antenna. The EMF emitted by the bulbs will cause a few electrons to move back and forth in the RETURN cable adding to those coming from the sample response. There are other sources of noise, error, or parasitics that accompany an MR Task execution. Below is a list of those error sources and how to compensate for them.

Ambient EMF

The RETURN input of each Precision tester is set up as a virtual ground with a coaxial cable input. The shield of the coaxial cable is connected to the virtual ground amplifier ground reference. Periodic EMF signals picked up by coax cables are picked up equally by the center conduction *and* the shield. The virtual ground amplifier of the RETURN input subtracts its reference ground from the incoming signal on the center conductor of the coaxial cable. This differencing subtracts out the majority of the external EMF transmitted in the ambient environment of the laboratory because that EMF couples into both conductors of the coaxial cable.

The same is not true for non-coaxial wire. It has no shield so there will be no balance signal to subtract out the ambient EMF. This is especially true of the magnetic driver coil which will efficiently pick up the ambient EMF, broadcast it into the sample and the wires connected to the sample, and put the EMF signal on the ground of the DRIVE circuitry which is loosely connected to the RETURN circuitry. Without putting the driver coil and the sample in a Faraday cage, ambient EMF will find its way into the charge measurement. Nonetheless, careful placement of the coil and sample and the minimum use of bare wire to connect the sample to the DRIVE and RETURN inputs will reduce the noise level well below the signal level.

NOTE: The ambient EMF, especially 60Hz or 50Hz power signals, are *not* filtered out of the measured data by Vision. The sample response will have some intrinsic frequencies in this range so a filter would distort the results.

For best results without a Faraday cage or electrical shield box, place the magnetic coil over a non-magnetic metal plate and ground the plate to the green banana plug on the rear of the tester. This will create a small bubble around the coil that reduces EMF intrusion.

Inducted Current

A changing magnetic field will induce current into a wire. This includes the cables connecting the sample to the RETURN input. Again, this effect will be far worse for standard wire than for coax cable so minimize the length of non-coaxial cable connected to the sample. Also, adjust the orientation of the wires coming into the magnetic field region to minimize the induced current. Nevertheless, the test fixture should always be tested for induced current. This is accomplished by replacing the sample with a linear capacitor of the same effective capacitance as the sample and running the intended test procedure. Any response to the magnetic field measured this way must originate from induced current and can be subtracted from later measurements of the sample. This procedure must be repeated any time the sample is moved or the geometry of the test setup is changed. There will be more discussion of measuring induced current later in this document.

The induced current is linearly related to the rate of change of the magnetic field. The faster the test, the greater the amplitude of induced current. This characteristic can be used to verify that a parasitic charge measured from a linear capacitor is indeed induced current. It also means that the effect of induced current can be reduced by slowing down the test frequency.

Physical Motion

The magnetic field driven by the tester will apply force to the sample. *If the sample moves in response to the force, the resulting measurement will not be correct.* The sample holder or sample mount must be rigid.

Non-magnetic Fixture

Any magnetic metal in the vicinity of the sample will change the shape and amplitude of the magnetic field around the sample. This may be mitigated by using a Gauss meter to measure the B-field strength at the sample but it is best to not allow any magnetic material within the test fixture during MR Task execution.

Test Frequency

The MR Task is a *static* test. It produces the magnetic field in steps, stopping after each step to wait until the drive signal and the sample have settle into a steady state before capturing the new charge state of the sample. The inductance of the driver magnetic coil will cause a phase delay between the time at which a new voltage step appears on the input of the current amplifier and the time at which the new magnetic field value stabilizes across the sample. For accuracy during MR Task execution, the time constant of the current amplifier and magnetic coil together must be much shorter than the delay period for each step. The Premier II and Multiferoic testers acquire 1000 points during a test slower than 1ms in period. All of other tester models acquire 500 points. The delay period for each step will be the test period divided by the number of points. Therefore, a Premier II executing a 1 second magnetic hysteresis will capture a measurement every millisecond. Nominally, the current amplifier and coil should settle faster than 1ms. The sample *will respond to the magnetic field* at its location so a Gauss meter located at the sample will eliminate any distortion that might arise from the phase delay between the DRIVE output stimulus signal and the actual magnetic field at the sample. If the magnetic field at the sample is not measured but instead is estimated with the coefficients described earlier, there may be some distortion in the results due to this phase delay.

In most cases the sample will be much faster than the test frequency so it will introduce little distortion in the measurement. Nonetheless, large samples with resonant frequencies below $1/100^{\text{th}}$ of the test frequency will introduce some distortion in the measurement results as the sample response lags behind the magnetic stimulus. Even though phase delay in the magnetic field may be eliminated using a Gauss meter probe at the sample, the sample itself may introduce a small phase delay if the test frequency is closer than 1% of

the resonant frequency of the sample. The best method to defeat this distortion is to use the slowest possible test period.

NOTE: Due to the myriad distortions that might occur from coil inductance, phase delay, resonant frequencies, amplifier current limits, etc., Radiant has limited the test speed for the MR Task to the range of 10 Hz down to 1 Hz.

Recommended Test Flow

- 1) Determine the voltage-to-current coefficient for the current amplifier.
- 2) Determine the current-to-B-field coefficient for the driver coil(s). Usually, this is a calibrated value supplied with the coil by the manufacturer.
- 3) Determine mathematically the geometry coefficient for the sample's relationship to the driver coil.
- 4) If the sample has a magnet or magnets as part of its construction, independently measure the magnetic moment m of the magnet(s) in order to later qualify the results.
- 5) If the sample has a piezoelectric element as part of its construction, independently measure the piezoelectric constant of that element in order to later qualify the results.
- 6) Place the sample at its point of measurement.
 - a. Ensure that there is no magnetic metal in the fixture holding the sample.
 - b. Ensure that the platform holding the sample is rigid.
 - c. Ensure that the location and orientation of the cables connected to the sample minimize inducted current during a test.
 - d. As much as possible, ensure that the cables connecting the sample to the RETURN input of the tester are shielded. (See Figure 2 through 7.) Ground the cable shields to the shield connection of the RETURN BNC on the tester.
- 7) If available connect magnetic field sensors to the tester.
 - a. If available, place a Gauss meter probe as near as possible to the sample location and orient the probe to be perpendicular to the driven magnetic field. Connect the voltage output of the Gauss meter to the SENSOR 2 input of the tester using coaxial cable.
 - b. If a Gauss meter is not available but a current sensor is, place the current sensor in-line between the current amplifier and the driver coil(s) and connect the voltage output of the current sensor to the SENSOR 1 input of the tester.
- 8) If a field coil is to be used to generate a DC magnetic bias, connect an I2C DAC Controller to the field coil amplifier input and record the I²C address of the controller.
- 9) If an electric bias is to be applied across the sample capacitor, connect an I2C DAC Controller to the one side of the sample using coax cable. (See Figure 7.) Connect the other side of the sample to the RETURN input.

NOTE: If more than one I²C DAC Controller is to be connected to the tester, use an I²C Spider Board from Radiant.

- 10) Open the MR Task setup menu and enter the three coefficients for generating the magnetic field. Also, if a current sensor or Gauss meter will measure the magnetic field, enable the SENSOR1 or SENSOR2 operation in the menu and set the conversion factor to convert the voltage on the SENSOR input to the appropriate units of magnetic field.
 - a. If neither SENSOR1 nor SENSOR2 are activated for a test, the MR Task will estimate the driven magnetic field using the current amplifier, magnetic coil, and geometry coefficients.
- 11) If a field coil is to be used, enter the I²C address of its controller into that section of the MR Task setup menu. Also set the strength of the bias field desired for the test.
- 12) If a voltage bias is to be placed across the sample, enter the I²C address of its controller into an I2C Volts Task placed before the MR Task in the Vision Editor. Place a second I2C Volts Task after the MR Task to return the sample bias voltage back to zero volts at the end of the test.
 - a. If no bias is to be applied to the sample during an MR Task execution, ground that side of the sample to the shield of the RETURN BNC.
- 13) Measure the small signal capacitance of the sample at 0V. Select a linear capacitor near the same value. Substitute this linear capacitor for the sample and run MR tests at the intended test frequencies and magnetic fields while the capacitor is placed at the same location and orientation at which the sample will be tested. The linear capacitor connected in place of the sample allows induced current flow between the two cables as would occur with the sample in place.
 - a. Adjust the sample cables if necessary to reduce the inducted current response.
 - b. Save the measured results for later subtraction from measurements of the sample.
- 14) Replace the sample and make the same measurements using the MR Task.
 - a. Note that the MR Task can be placed inside a Branch Loop in the Vision Editor and the DC Bias Field, the test period, or the amplitude of the magnetic field stimulus can be varied systematically in each branch execution.
- 15) If the induced current measured in Step 10 above is large enough to affect the results measured in Step 11, subtract the induced measurement from the sample measurement. (See the next section.)

Vision Test Definition

The MR Task may be run by itself as a QuikLook execution or in a Test Definition. To eliminate inducted charge from the MR Task sample measurements, the MR task should be executed with the linear coupling capacitor as previously described. The result should then be exported as a VIS file. This can be done by recalling the measurement from the Vision Archive and pressing the EXPORT button.



Fig. 8: The EXPORT button on the Data Display Panel for the MR Task.

The EXPORT SETUP window provides several choices of file format. The Vision file format can be imported into a task in a test definition and treated as acquired data during test execution.

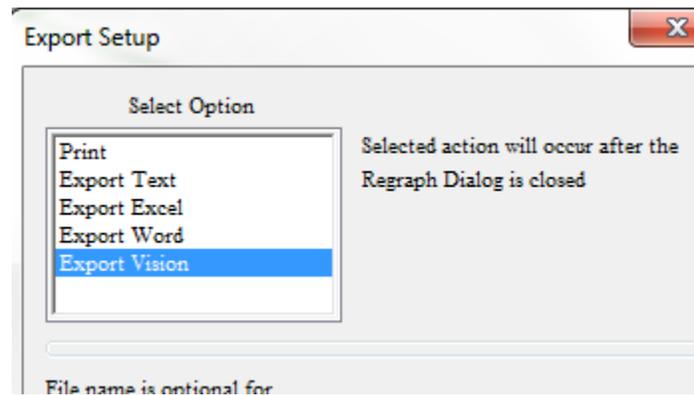


Fig. 9: The EXPORT Vision selection.

The Test Definition to measure the sample and subtract the inducted charge has three steps:

Test Definition in the Vision Editor

- MR Task – Measure Sample
- MR Task – Import Vision file of the measured inducted charge
- Two Trace Math Filter – Subtract the inducted charge from the sample measurement.

In each execution of this test definition, the Archive record will hold the sample measurement, the recalled inducted charge measurement, and the corrected sample measurement.

If an I2C DAC Controller is used to apply a bias voltage across the sample during a test, two I2C Volts tasks must be added to the Test Definition.

Test Definition in the Vision Editor

- I2C Volts Task – Set the bias voltage across the sample
- MR Task – Measure Sample
- MR Task – Import Vision file of the measured inducted charge
- I2C Volts Task – Return the sample bias voltage to zero

Note that if an I2C DAC Controller is used to set a DC magnetic bias field across the sample, it is controlled from within the MR Task.

A Branch Task may be used to make multiple measurements sequentially while varying one or more of the test parameters.

Test Definition in the Vision Editor

- I2C Volts Task – Set the bias voltage across the sample
- MR Task – Measure Sample
- MR Task – Import Vision file of the measured inducted charge
- I2C Volts Task – Return the bias voltage to zero
- Branch Task – Jump to the I2C Volts Task.

The I2C bias voltage may be adjusted as a function of loop number. The MR Task will allow the user to vary test period, the magnetic stimulus amplitude, or the DC magnetic field bias in each loop. To adjust these parameters in a loop, press the ADJUST PARAMETERS button on each setup menu.

Example with Radiant Reference Sample

The sample in Figure 1 was subjected to MR Task execution using an MH-6 Helmholtz coil from Lake Shore Cryogenics, Inc., a BOP36-6 current amplifier from Kepco, and a Precision LC ferroelectric tester. The BOP36-6 can generate 6 amps up to 36 volts but is limited to about 10 Hz. The maximum current allowed for the MH-6 is two amps so the positive and negative current limits for the BOP36-6 were set to those values.

The sample was placed on an electronics perf board and held in place in the Helmholtz coil region by alligator clips. The alligator clips were paramagnetic so they were a source of error in the measurement. The electronic perf board plus the long lever arm holding the sample were not perfectly rigid so this was another possible source of error in measuring the response of the sample.

NOTE: the charge measurement of the Precision tester is extremely accurate. The term “error” in this case means that the measured response deviates from the predicted response due to interference by error sources that affect the driven magnetic field or the sample charge generation in a way that cannot be accounted for in the prediction. Accuracy is improved by eliminating these error sources.

Neither a Gauss meter nor a current meter was available for the experiment so the magnetic field in each test was estimated by the MR Task from the test fixture coefficients. The Kepco BOP36-6 was determined to have a voltage-to-current coefficient of 0.5714 amps/volt. The MH-6 Helmholtz coil was calibrated by Lake Shore to have a current-to-B-field coefficient of 26.76 Gauss/amp. These values were entered into

the MR Task setup menu and a maximum magnetic field of 45 Gauss was requested for each test. The geometry coefficient was left at unity for all tests. Separately from the measurement cycles, we measured the current flow in the coil during a test cycle and found from the current during the cycle that the coil peaked at 48.15 Gauss instead of the requested 45 Gauss.

The capacitor on the reference sample was a Sensor Die. That capacitor has an area of 4mm x 4mm (0.16cm²). Manually applying force and torque to the sample, the following effective piezoelectric coefficients were determined:

- 1) d_p 650±40 pC/N
- 2) d_t 765 pC/N

Normally, the clamped d_{33} value for the 1μ-thick PNZT in the Sensor Die is 60pC/N. However, the substrate on which the capacitor rests can bend into an arc or twist, amplifying the piezoelectric effect. The value of d_p includes any bending moment to the capacitor substrate so it is larger than the d_{33} piezoelectric constant for the 4/20/80 PNZT. The same is true for d_t , which generates charge from shearing forces that occur within the ferroelectric capacitor when its substrate is twisted like a pretzel as a torque to the magnet will cause.

A set of rare-earth magnets were purchased from Radio Shack. The magnets had the dimensions of

Diameter	5mm
Height	1.5mm

They were specified to have a B-field at their poles of 1.08 Tesla but the accuracy of this specification is unknown. One magnet was glued to the surface of the Sensor capacitor and three more were placed on top of the anchor capacitor, held in place by their intrinsic magnetic fields. This is another source of error in the measurement since the top three magnets were not rigidly glued to the anchor magnet. Given their dimensions and surface B-field, the m of the magnet stack on the Sensor capacitor was estimated to be

$$m = 0.146 \text{ Am}^2 \tag{Eq(24)}$$

using the ideal magnetic dipole equation. The accuracy of this prediction is unknown. A more accurate value would have been determined by directly measuring the magnetic moment of the magnets using the classic magnetic moment measurement in the Helmholtz coil.

Since the reference sample was a magnetoelectric composite device, there are four possible geometries at which it may be measured.

- 1) In the Helmholtz volume of uniformity with the m axis *parallel* to the driven B-field. This should generate no response since there is no gradient to the magnetic field at that point.
- 2) In the Helmholtz volume of uniformity with the m axis *perpendicular* to the driven B-field. This should generate the strongest torque-driven response.
- 3) Outside the Helmholtz coil with the m axis *parallel* to the driven B-field. Outside the Helmholtz coil the magnetic field should have a gradient and the sample should generate a response.

- 4) Outside the Helmholtz coil with the m axis *perpendicular* to the driven B-field. Outside the Helmholtz coil the magnetic field torque should still drive the reference sample and the sample should generate a response.

The test fixture with the sample in Position 2 located within the volume of uniformity with the magnet axis perpendicular to the Helmholtz coil B-field is shown in Figure 10.



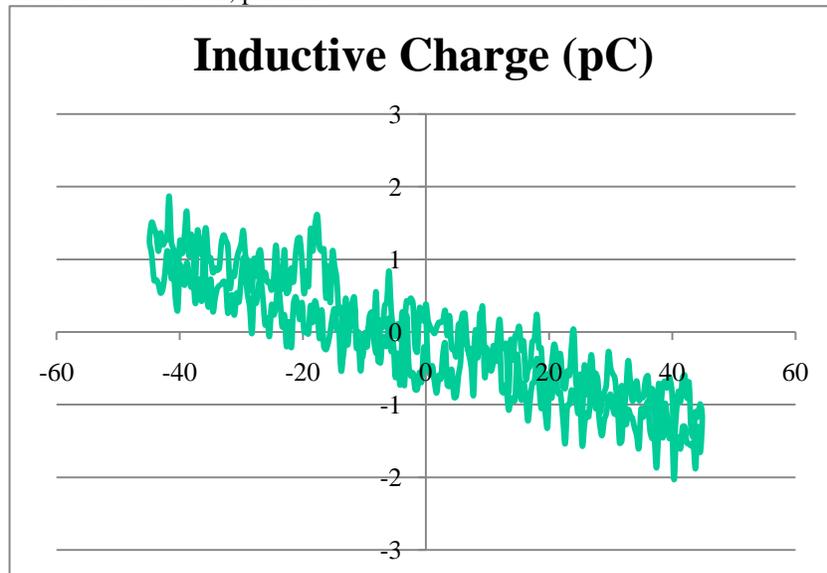
Fig. 10a: Precision LC and Kepco 36-6 current amplifier.



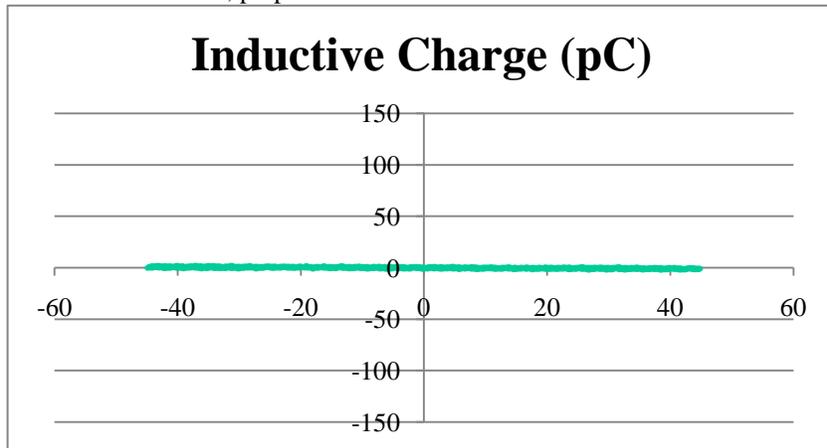
Fig. 10b: Reference Sample in Helmholtz Coil.

The Sensor capacitor has a small-signal capacitance of roughly 92nF. A 100nF capacitor was substituted for the sample to measure the inducted current. The measurements of inducted current for each of the four positions are shown below.

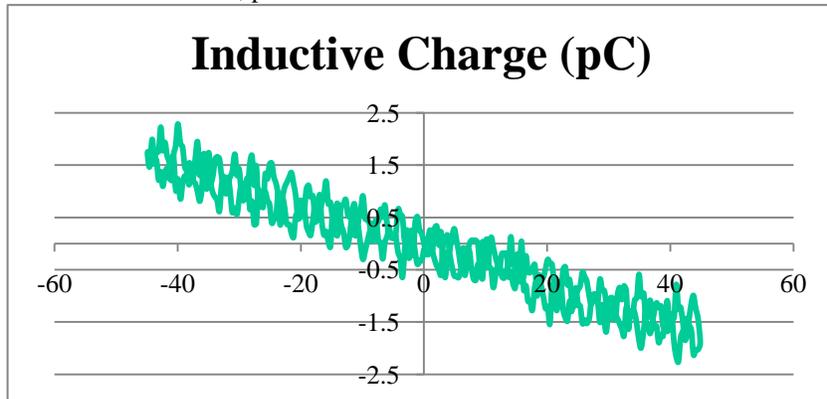
(a) Center Helmholtz coil, parallel



(b) Center Helmholtz coil, perpendicular



(c) Outside Helmholtz coil, parallel



(d) Outside Helmholtz coil, perpendicular

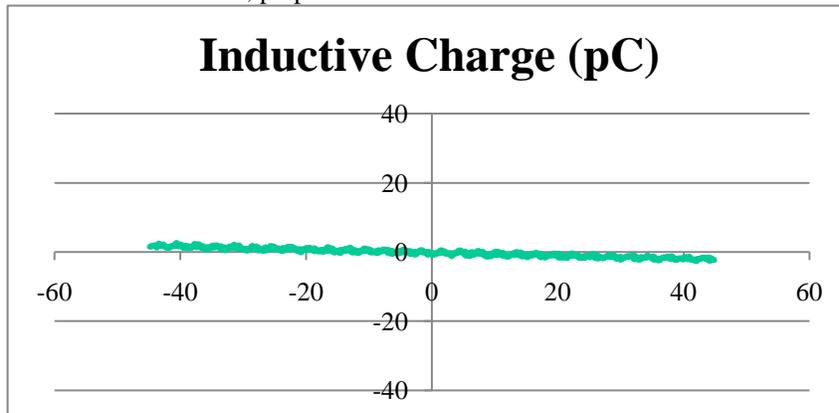
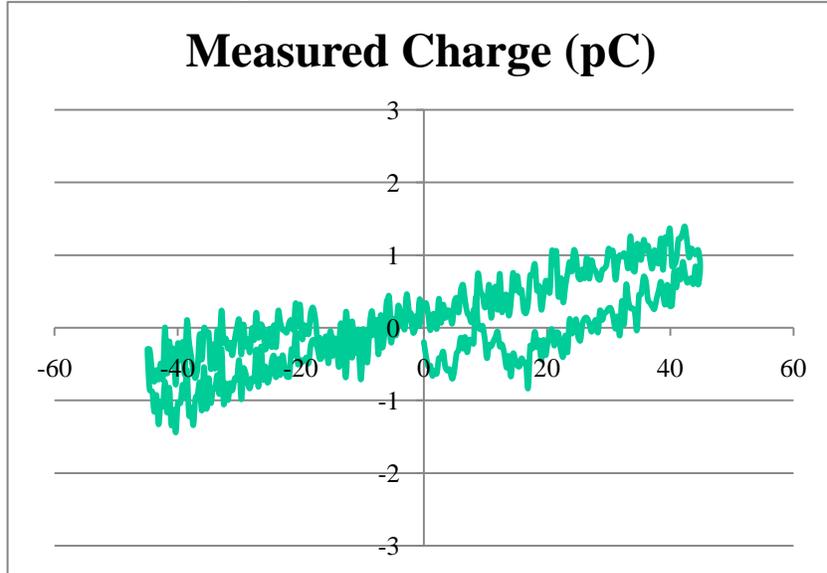


Fig. 9: Induced current for positions 1 (a) through 4 (d).

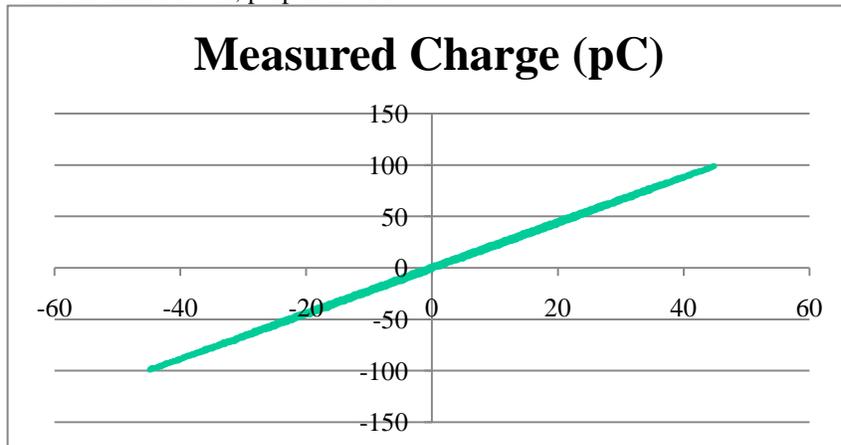
Note that the plots are scaled to the amplitude of their respective sample measurement. The induced charge ranged from 1pC to 2pC.

The measurements of the sample acquired at each location are shown in Figure 10.

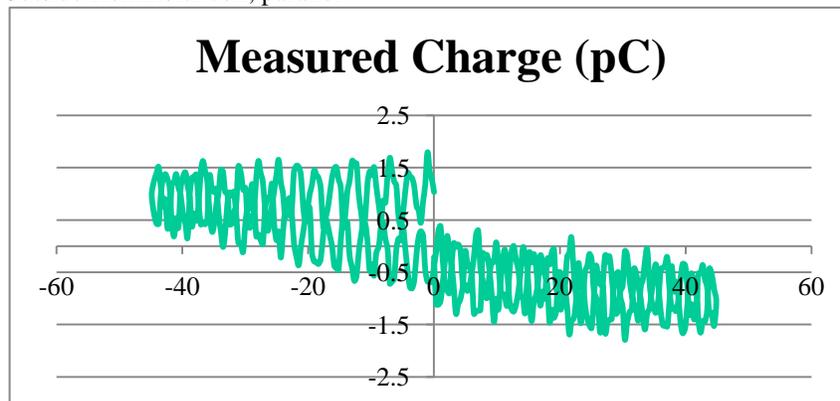
(a) Center Helmholtz coil, parallel



(b) Center Helmholtz coil, perpendicular



(c) Outside Helmholtz coil, parallel



(d) Outside Helmholtz coil, perpendicular

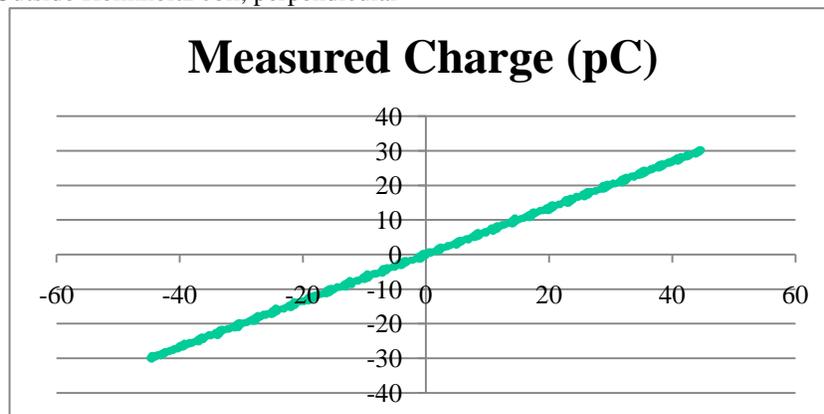
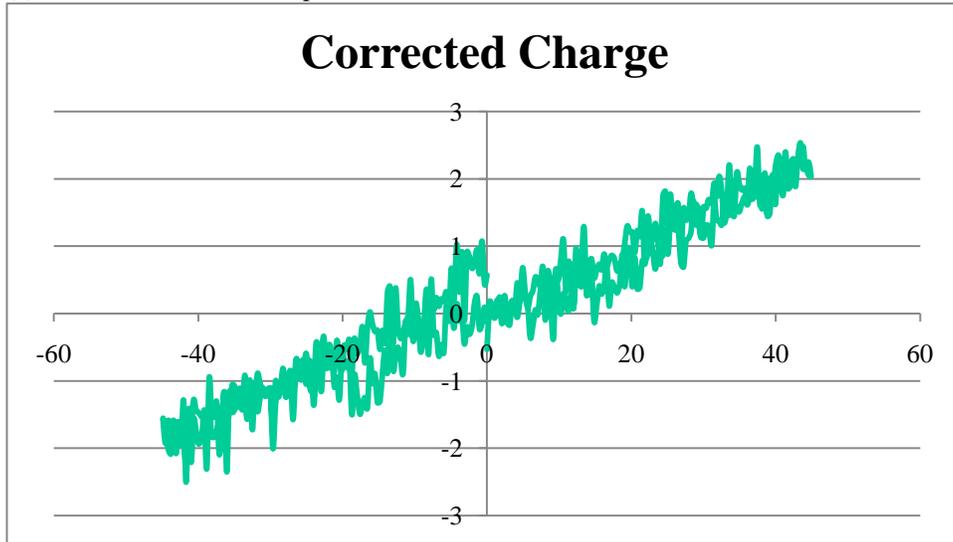


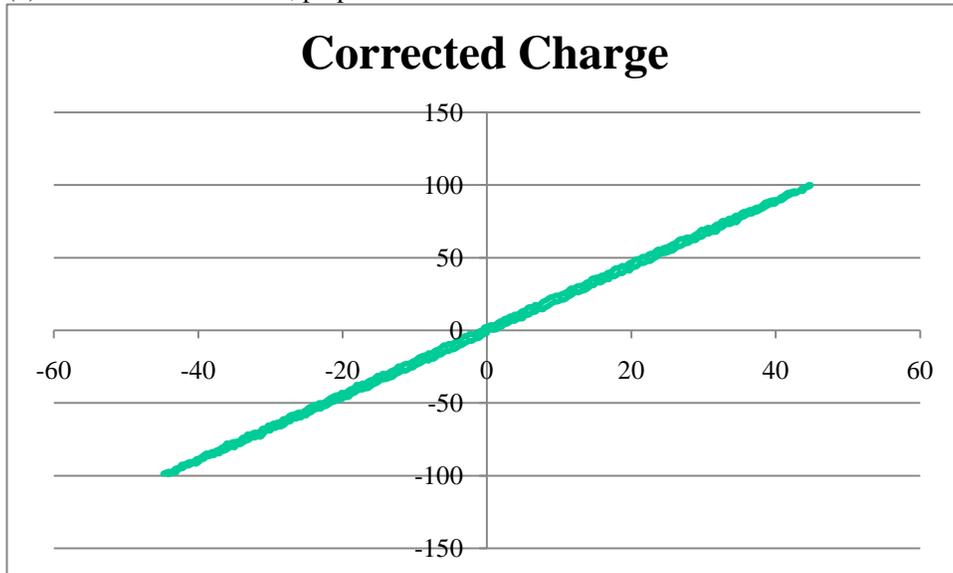
Fig. 10: Sample measurement for positions 1 (a) through 4 (d).

The measurement of each sample with inducted current subtracted out is shown in Figure 11.

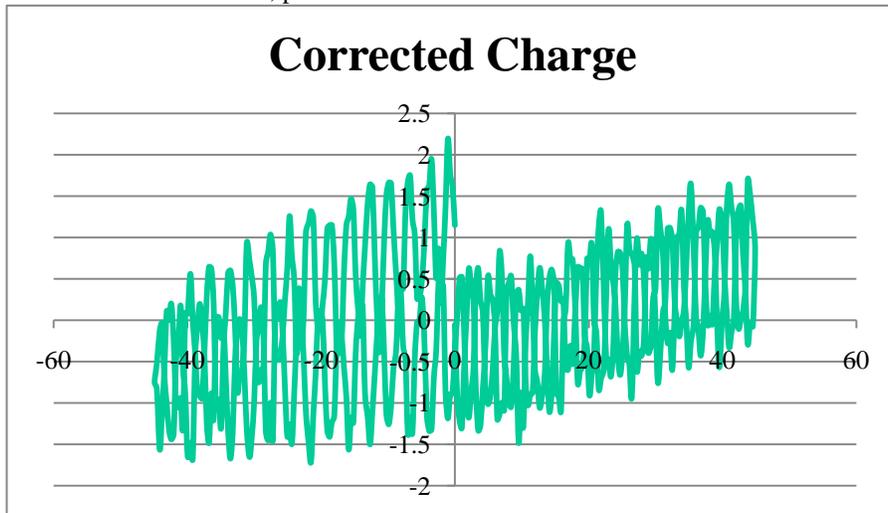
(a) Center Helmholtz coil, parallel



(b) Center Helmholtz coil, perpendicular



(c) Outside Helmholtz coil, parallel



(d) Outside Helmholtz coil, perpendicular

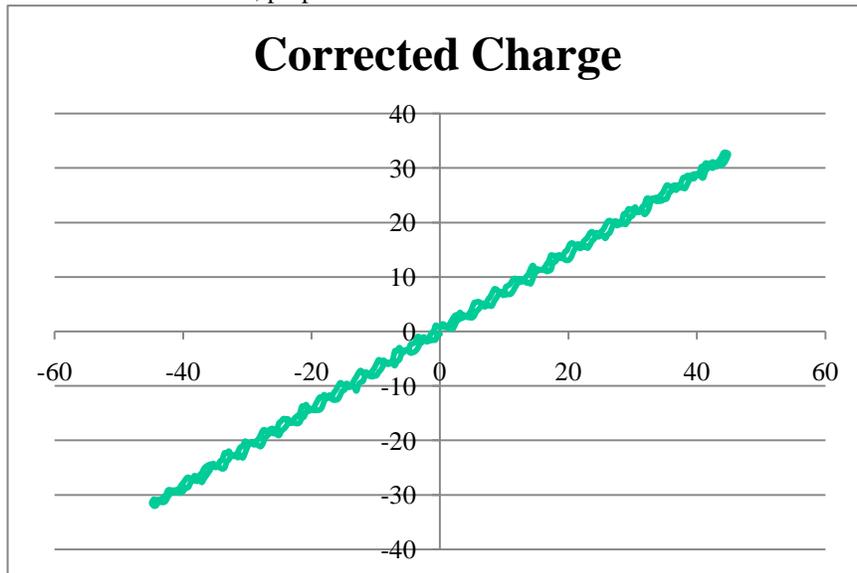


Fig. 11: Sample response corrected for inducted current for positions 1 (a) through 4 (d).

The EMF of the room lights and local power supplies is visible in all of the results except for the perpendicular measurement inside the Helmholtz coil. In that case, the amount of signal generated by the sample swamped the room EMF noise. The ambient EMF is only slightly visible in the torque measurement made outside the Helmholtz coil at Position 4.

Analysis

Using B-field values estimated from the test fixture coefficients and combining them with the piezoelectric constants associated with each of the four positions, we calculated the maximum charge that should be generated by the sample in the four positions. (See Addendum at the end of this application note.) The predicted values and the measured values corrected for inducted charge are given in Table 1.

Position	Inducted Charge pC	Measured & Corrected pC	Predicted pC	Error pC	%error vs max
Center of coil, parallel	-1.2	2	0	2	2.0%
Center of coil, perpendicular	-1.0	101	89.6	0.5	11.3%
Outside of coil, parallel	-2.3	+1	2.42*	1.75	1.72%
Outside of coil, perpendicular	-1.9	32	27.7	0.9	15.5%

Table 1: Table of Results vs. Predictions

- The N/S orientation of the magnet on the reference sample was not determined so there is a sign ambiguity as to the direction of the charge generation for force generated by the magnetic gradient at 1.5R. The torque response, on the other hand, is a rotation that is sign independent, meaning that the piezoelectric capacitor should generate charge of the same sign independent of the sign of the torque as long as the magnet was always oriented in the same direction in the plane perpendicular to the B-field of the coil.

The amplitude of the inducted charge for all measurements amounted to no more than 2.2% of the maximum signal measured during the test, 101pC. The two gradient-force measurements where the magnet axis and the B-field axis were aligned produced ambiguous results. The two torque-force measurements produce far larger amounts of charge with values very close to the predicted values. We interpret the gradient measurements in Table 1 to indicate that the error bars on the measurements should be approximately ± 2 pC in absolute value for the test fixture used in the experiment. Both of the gradient-force measurements had predicted values at or below this limit, meaning that the amounts of charge they should have generated were below the level of accurate detectability by the Precision LC. The charge resolution of the Precision Premier II and Precision Multiferroic testers is 38 times larger than that of the LC so they should be able to measure accurately at the 2pC level.

The torque equation, Equation 11, indicates that the amount of charge generated by the sample should scale linearly with the amplitude of the B-field. This appears to be the case. We used Equation 11 combined with Equation 12 and Equation 14 to determine the B-field in the center of the Helmholtz coil vs the B-field at a distance of 1.5 times the radius of the Helmholtz coil from the center of the coil. The mathematical ratio of the two B-fields is 0.32. The two torque measurements made at those two locations had a ratio of 0.32, indicating that the charge being measured during the test was definitely generated by stimulus from the magnetic coil.

The two torque measurements differed from the predicted values by 11% to 15%. Given the potential error sources described earlier, this difference is within acceptable range. The measurement values are absolute values, electrons having been counted by the tester. Most likely the difference arises from inadequacy in our prediction of the expected value. We will execute the tests again using a Gauss meter to ensure a more accurate measure of the magnetic field. We will also more accurately determine the piezoelectric constants and magnetic moment for the sample and build a more rigid, and less magnetic, sample holder for the driver coil.

Conclusion

The Magnetolectric Response Task in Vision running on a Precision LC was used successfully to measure the response of a magnetolectric composite reference device consisting of a magnet glued to a piezoelectric capacitor. The sample generated between 30pC and 101pC with a high signal-to-noise ratio when arranged so that the driven magnetic field generated a torque on the sample's magnet. When arranged geometrically so the gradient of the magnetic field produced the force, any charge generated by the sample was not accurately measureable, establishing a measurement floor of 2pC for this test fixture using a Precision LC. This minimum resolution can be improved by using a Premier II or Multiferroic tester, both of which have higher charge resolution, and by generating a stronger magnetic field during the test. The piezoelectric performance of the sample was characterized prior to the measurement in order to predict the expected charge to be generated by the test in the various sample geometries. The measured values, corrected for inducted charge in the sample cables, were within 15% or less of the predicted values. Based on these results, magnetolectric measurements of samples that generate 30pC or more of charge may be executed with 15% or less error using a Precision LC at 50 Gauss magnetic field strength. The prediction error may be reduced by careful attention to the test fixture characteristics and by more accurately determining the magnetic field at the sample.

ADDENDUM:

Units

H	Amp turns/meter	A/m
B	Tesla	T or N/Am
<i>m</i>	Amp meters squared	Am ²
μ ₀	permeability	N/A ²
G	Gauss	1x10 ⁻⁴ Tesla
Oe	Oersted	1000/4π x H
α	Magnetolectric Coupling Coefficient	C/m ² per Oersted
d	Piezoelectric Coupling Coefficient	pC/N (picocoulombs per Newton)

Units of Equations

$$\mathbf{P} = \alpha \mathbf{H} \quad \text{Eq(5)}$$

C/m ²	=	[C/m ² per Oersted] x Oersted
C/m ²	=	C/m ²

$$m = 2\pi \mathbf{r}^3 \mathbf{B} / \mu_0 \quad \text{Eq(18)}$$

Am ²	=	m ³ * [N/Am] / [N/A ²]
Am ²	=	[N/N] * [A ² /A] * [m ³ / m]
Am ²	=	Am ²

$$Q_p = d_p * m * \delta B / \delta x \quad \text{[parallel B-fields] Eq(10)}$$

pC	=	[pC/N] * [Am ²] * [N/Am / m]
pC	=	pC [N/N] * [Am ²] / [Am ²]
pC	=	pC

$$Q_\tau = d_\tau * (m * B / L_{\text{magnet}}) \quad \text{[perpendicular B-fields] Eq(11)}$$

pC	=	[pC/N] * [Am ²] * [N/Am] / [m]
pC	=	pC

m for the Magnet on the Reference Sample using the Ideal Magnetic Dipole Equation

$$m = 2\pi \mathbf{B} \mathbf{r}^3 / \mu_0 \quad \text{Eq(18)}$$

$$m = 2\pi (1.08\text{T}) (0.003)^3 / 4\pi \times 10^{-7}$$

$$m = 0.146 \text{ Am}^2$$

$\delta\mathbf{B}/\delta x$ for Single Coil with N Loops

$$\mathbf{H} = \text{NIR}^2 / 2(\text{R}^2 + \text{x}^2)^{3/2}$$

$$\mathbf{B} = \frac{1}{2} \mu_0 \text{NIR}^2 * (\text{R}^2 + \text{x}^2)^{-3/2}$$

$$\delta\mathbf{B}/\delta x = \frac{1}{2} \mu_0 \text{NIR}^2 * \delta(\text{R}^2 + \text{x}^2)^{-3/2} / \delta x$$

$$\delta\mathbf{B}/\delta x = \frac{1}{2} \mu_0 \text{NIR}^2 * -3/2 * (\text{R}^2 + \text{x}^2)^{-5/2} * \delta(\text{R}^2 + \text{x}^2) / \delta x$$

$$\delta\mathbf{B}/\delta x = \frac{1}{2} \mu_0 \text{NIR}^2 * -3/2 * (\text{R}^2 + \text{x}^2)^{-5/2} * 2x$$

$$\delta\mathbf{B}/\delta x = (-3/2) \mu_0 \text{NIR}^2 * [x / (\text{R}^2 + \text{x}^2)^{5/2}]$$

Predicted Charge for Gradient Magnetic Force at 1.5R from Helmholtz Coil

To find the gradient of the magnetic field at 1.5R (R = radius of Helmholtz coil), solve $\delta\mathbf{B}/\delta x$ for one coil at 1R and a second coil at 2R and sum the values.

$$\delta\mathbf{B}/\delta x = (-3/2) \mu_0 \text{NIR}^2 * [x / (\text{R}^2 + \text{x}^2)^{5/2}]$$

Coil₁ at 1R:

$$\begin{aligned} &= (-3/2) \mu_0 \text{NIR}^2 * [\text{R} / (\text{R}^2 + \text{R}^2)^{5/2}] \\ &= (-3/2) \mu_0 \text{NIR}^3 / (2\text{R}^2)^{5/2} \\ &= (-3/2) \mu_0 \text{NIR}^3 / 2^{5/2} \text{R}^5 \\ &= -0.26 \mu_0 \text{NI} / \text{R}^2 \end{aligned}$$

Coil₂ at 2R:

$$\begin{aligned} &= (-3/2) \mu_0 \text{NIR}^2 * [2\text{R} / (\text{R}^2 + 4\text{R}^2)^{5/2}] \\ &= -3 \mu_0 \text{NIR}^3 / (5\text{R}^2)^{5/2} \\ &= -3 \mu_0 \text{NIR}^3 / 5^{5/2} \text{R}^5 \\ &= -0.054 \mu_0 \text{NI} / \text{R}^2 \end{aligned}$$

Total Gradient at 1.5R:

$$\begin{aligned} &= -0.265 \mu_0 \text{NI} / \text{R}^2 + -0.054 \mu_0 \text{NI} / \text{R}^2 \\ &= -0.319 \mu_0 \text{NI} / \text{R}^2 \end{aligned}$$

Lakeshore does not provide the number of turns for the MH-6 but the diameter of the loops was 6.6 inches and it generates 26.76×10^{-4} T at 1 amp. Equation 14 tells us the following relationship:

$$\begin{aligned} \text{B}(\text{center of Helmholtz coil}) &= 0.716 \mu_0 \text{NI} / \text{R} = 48.15 \times 10^{-4} \text{ T (corrected for current measurement)} \\ \mu_0 \text{NI} / \text{R} &= 48.15 \times 10^{-4} \text{ T} / 0.716 \\ \mu_0 \text{NI} / \text{R} &= 67.25 \times 10^{-4} \\ \mu_0 \text{NI} / \text{R}^2 &= 67.25 \times 10^{-4} / \text{R} = 67.25 \times 10^{-4} / 0.084 \text{ m} \\ \mu_0 \text{NI} / \text{R}^2 &= 0.08 \\ \therefore \delta\mathbf{B}/\delta x (x = 1.5\text{R}) &= -0.319 \mu_0 \text{NI} / \text{R}^2 = \mathbf{-0.0255 \text{ T/m}} \end{aligned}$$

$$Q_p = d_p * m * \delta B / \delta x$$

$$Q_p = 650 \text{ pC/N} * 0.146 \text{ Am}^2 * -0.0255 \text{ T/m}$$

$$Q_p = -2.42 \text{ pC (at } x = 1.5R)$$

Predicted Charge for Magnetic Torque Effect

$$Q_\tau = d_\tau * (m * B / L_{\text{magnet}}) \quad [\text{perpendicular } B\text{-fields}] \quad \text{Eq(11)}$$

@ x=0

$$B = 48.15 \text{ T (corrected for current measurement)}$$

$$Q_\tau = 765 \text{ pC/N} * (0.146 \text{ Am}^2 * 48.15 \times 10^{-4} \text{ T} / 0.006 \text{ m})$$

$$Q_\tau = 89.6 \text{ pC}$$

@ x=1.5R

To find the amplitude of the magnetic field at 1.5R (R = radius of Helmholtz coil), solve for **B** for one coil at 1R and a second coil at 2R and sum the values.

$$B = \mu_0 N I R^2 / 2(R^2 + x^2)^{3/2} \quad \text{Eq(12)}$$

$$B(1.5R) = \frac{1}{2} \mu_0 N I R^2 [(R^2 + R^2)^{-3/2} + (R^2 + 4R^2)^{-3/2}]$$

$$B(1.5R) = \frac{1}{2} \mu_0 N I R^2 [(2R^2)^{-3/2} + (5R^2)^{-3/2}]$$

$$B(1.5R) = \frac{1}{2} \mu_0 N I R^2 [(2^{-3/2} R^{-3}) + (5^{-3/2} R^{-3})]$$

$$B(1.5R) = \frac{1}{2} \mu_0 N I / R [2^{-3/2} + 5^{-3/2}]$$

$$B(1.5R) = 0.2215 \mu_0 N I / R$$

$$B(1.5R) = 0.2215 * 67.25 \times 10^{-4}$$

$$B(1.5R) = 14.9 \times 10^{-4}$$

The ratio of the B-field in the center of the Helmholtz coil to that of the B-field at 1.5R from the center of the Helmholtz coil is

$$B_0 / B^{1.5} = 48.15 \times 10^{-4} \text{ T} / 14.9 \times 10^{-4} \text{ T}$$

$$B_0 / B^{1.5} = 0.32$$

$$Q_\tau = 765 \text{ pC/N} * (0.146 \text{ Am}^2 * 14.9 \times 10^{-4} \text{ T/A} / 0.006 \text{ m})$$

$$Q_\tau = 27.7 \text{ pC}$$

Ratio of Predicted Gradient and Torque generated Charge at 1.5R

$$Q_p / Q_\tau = -2.42 \text{ pC} / 27.7 \text{ pC}$$

$$Q_p / Q_\tau = -0.087$$