Application Note

Application for Precision Impedance Meters in a Standards Laboratory

The QuadTech Model 7000 Series Precision LCR Meter is an automatic instrument designed for the precise measurement of resistance, capacitance and inductance parameters and associated loss factors. It is ideally suited for use in calibration and standards laboratories and can assume many tasks previously performed only by high priced, difficult to use, manually-balanced impedance bridges and meters.

This application note describes some of the benefits of the QuadTech Model 7000 Series that are particularly useful in a calibration or standards laboratory environment. It also describes in more detail, some of the applications where these benefits can be applied and techniques for realizing maximum benefit from this "impedance calibration lab in a box."

Figure 1: QuadTech 7600 Precision LCR Meter

Precision Measurement Capability of the QuadTech Model 7000 Series

The measurements of highest precision in a standards lab are 1:1 comparisons of similar impedance standards, particularly comparisons between standards calibrated at the National Institute of Standards and Technology (NIST) and similar reference standards. This type of measurement requires an instrument with high measurement resolution and repeatability in order to detect parts-per-million (ppm) differences rather than instruments with extreme, direct-reading accuracy. In such applications, two standards of very nearly equal value are compared using "direct substitution"; they are measured sequentially and only the difference between them is determined. The resolution of the Model 7000 Series is 0.1ppm for the direct measured values and such direct reading measurements, at a one/second rate, have a typical standard deviation of 0.2ppm at 1kHz.

Averaging Capabilities

By using the instrument's **AVERAGING mode**, the standard deviation can be reduced by $1/\sqrt{N}$ where N is the number of measurements averaged. Thus, an average of 5 measurements or more reduces the standard deviation to under 1ppm. It is therefore usually easy to measure the difference between two impedances to better than 2ppm with the Model 7000 Series. Averaging many measurements takes time, yet an automatic impedance meter like the 7000 Series can take hundreds of averaged measurements in the time it takes to balance a high-resolution, manual bridge.

Measurement precision and confidence can be further improved by using the Model 7000 Series's **MEDIAN measurement mode**. In the median measurement mode, the instrument makes three measurements rather than one and discards the high and low results. The remaining median measurement value is used for display or further processing (such as averaging). Using a combination of averaging and median measurements not only increases basic measurement precision, but will also yield measurements that are independent of a large errors caused by line spikes or other non-Gaussian noise sources.

The **ppm resolution** of the 7000 Series is also not limited to values near full scale as is typically true on six-digit, manual bridge readouts. In the case of a manually balanced bridge, the resolution of a six-digit reading of 111111 is 9ppm. The 7000 Series does not discriminate against such values; it has the same 0.1ppm resolution at all values of all parameters including dissipation factor and quality factor (tangent of phase angle).

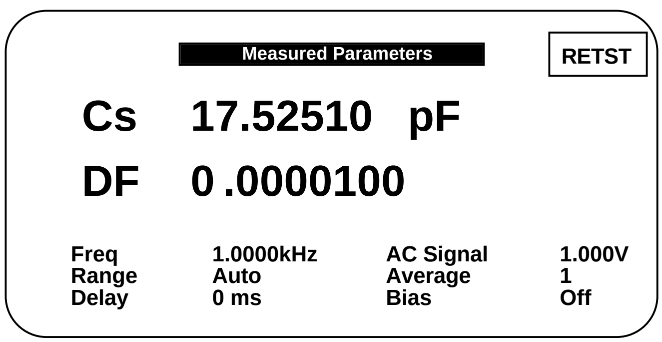

Figure 2: 7 Digit Resolution of Model 7000 Series

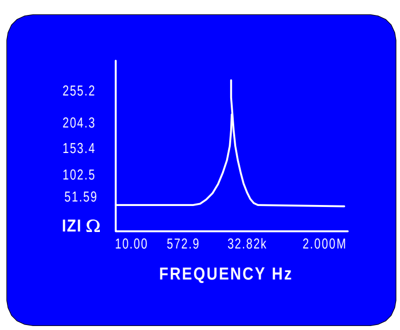

Figure 3: Measured Results in Graphical Form

Multi-Terminal Connection

An important feature of the Model 7000 Series generally not available with precision manual bridges is **multi-terminal connection** capability which allows both 4-terminal, Kelvin connections and 3-terminal, guarded connections to be made. This capability is particularly important if measurements of both very high-value and very low-value impedances are required. More-over, the automatic open and short-circuit zero correction capability of the Model 7000 Series augments its multi-terminal capability by enabling automatic subtracting out of the effects of unguarded stray capacitance and mutual inductance between connecting wires.

Obviously, automatic instruments such as the QuadTech 7000 Series have the significant advantage of speed, since a balancing procedure is not required. Balancing manual AC bridges is tiresome, time consuming and frequently requires highly skilled personnel. This is especially true when low-Q components are being measured as an annoying series of alternate balances of the two adjustments is often required to null a manual AC bridge.

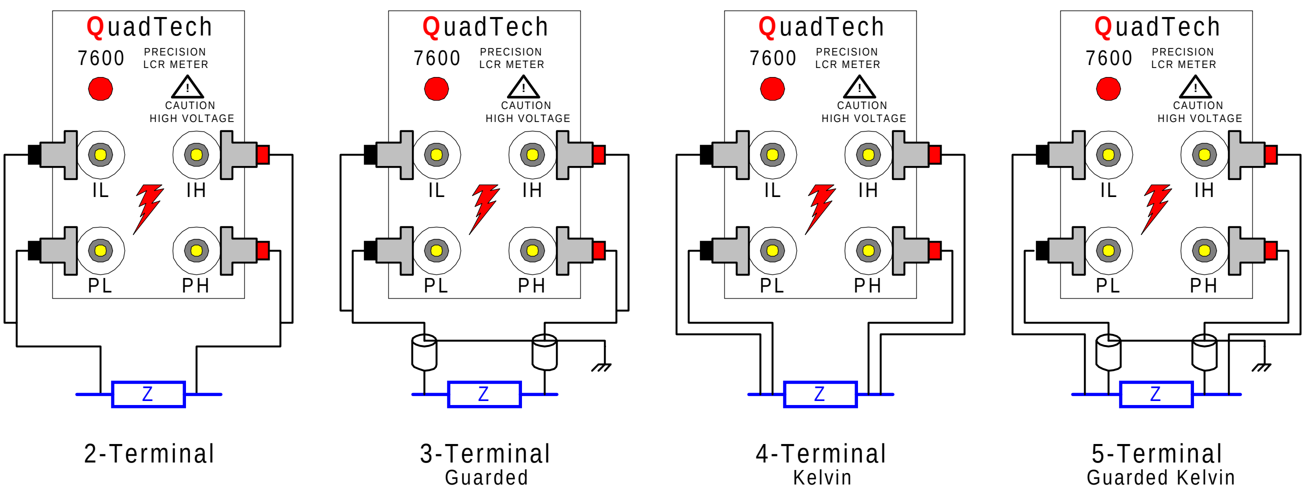

Figure 4: Multi-Terminal Connections

Another advantage of programmable instruments such as the Model 7000 Series, is the ability to create a **fully automated system** by utilizing the instrument's RS-232 and IEEE-488.2 bus interface capability. With a computer based system, required correction calculations can be made without the chance of human errors, especially the all-to-common recording problems with + and - signs. Suitably programmed, such systems can lead a measurement technician through complicated calibration processes with prompts and procedures that ensure proper measurement techniques and precise data manipulation. Calibration certificates and other records can also be printed thus avoiding the opportunity of making a mistakes in recording the results.

In many applications, the QuadTech Model 7000 Series unit can make better measurements than any other available manual or automatic bridge. In other cases, the Model 7000 Series instrument can satisfy a significant percent of precision measurement and calibrations needs, thus relieving highly skilled personnel and reducing the wear and tear on specialized, expensive lab instruments by saving them for only the most specialized measurement tasks.

Specific Model 7000 Series Applications

A made-to-order application for the Model 7000 Series that uses many of the features mentioned above is the **inter-comparison and scaling of inductance standards**. This application is particularly important because there has been no precision inductance bridge available with direct reading ppm or better resolution. Manual bridges that are available, lack direct-reading accuracy so balancing these bridges is a slow procedure. This is particularly true when measuring standards which have low Q values, especially at 100Hz , where many measurements must be made. Moreover, the effective AC resistance of these standards is primarily the resistance of copper wire which has a temperature coefficient of almost 4000 ppm/°C. Even a 1/100th of a degree change in the temperature of the wire due to ambient changes or applied power causes an annoying bridge unbalance which makes the inductance measurement difficult. The Model 7000 Series has no such problem; the resistance can change at any (reasonable) rate without affecting the inductance reading. Because of this and the 7000 Series's ease-of-use, it is ideal for making 1:1 comparison measurements on inductance standards.

Inductance Measurements

A 5-terminal (guarded Kelvin) capability would have been an advantage in calibrating these inductance standards, but because many were designed long before either 3-terminal or 4-terminal capability was available on an inductance bridge, NIST uses a grounded, 2-terminal connection. With early precision meters, ground was guard, not one of the main connections, but this did not cause a problem. The only thing to remember, when measuring some Standard Inductors is to tie the case to its LOW terminal (with a shorting link, when provided) and to insulate the case from ground. This keeps the internal stray capacitances that effect high-inductance measurements the same as the 2-terminal calibration by NIST.

Standard inductors are particularly hard to scale in value by combining two or more units in series or parallel (as is done with resistors) because of their size, their low Q values and the stray capacitances involved when two are connected together. Transformer-ratio-arm bridges, capable of precise scaling, are not available for inductance measurements. They can be made from commercially available parts, but are difficult to construct and use. Fortunately, extreme accuracy is not required because the best NIST calibrations have an estimated uncertainty of .02%. However, ratio measurements used to scale these calibrations should be much tighter to avoid adding errors. Ratio measurements in the magnitude of 2:1, made on the 7000 Series on a single measurement range typically have errors less than 20ppm. This allows comparisons of inductors of intermediate value to be compared against the even decade values with negligible added error. Scaling calibrations over a wider range are less accurate because a range change may be required that may introduce a non-linearity error. In this case errors of 50ppm at 1kHz over the basic overall range of the instrument are possible.

High-Capacitance Measurements with the Model 7000 Series

Manual precision capacitance bridges typically can measure up to 1uF with high accuracy. This range can be extended somewhat by using external standards, but the accuracy deteriorates rapidly as the capacitance is increased because of the inductance of the wiring and the leakage inductance of the ratio transformer used in the bridge. These 3-terminal bridges (with a guard) have single connections made to each end of the capacitor being measured. For good accuracy at higher values, 4-terminal (Kelvin) connections are needed to remove the effects of self-inductance. Automatic short-circuit zero corrections are a good way to remove the remaining effects of mutual inductance between leads.

The 7000 Series has the capability of making 4-terminal connections and auto zeroing plus extremely range and excellent accuracy. The normal range of the 7000 Series extends to 10 Farads, so measuring a 1F capacitor with fairly good accuracy at 100Hz is well within its capabilities if proper zeroing is performed. The automatic zeroing process is performed at 10 frequencies over the 7000 Series usable frequency range yielding an accuracy of about 1% for 1F measurements at 100Hz. When properly zeroed the accuracy of extreme values depends mainly on the repeatability, which can be improved by averaging. For example, 10 measurements averaged would further improve the accuracy in the order of 50%. And yes, there are standards of capacitance with 1F values. More common are measurements on standards of lower values, between 1uF and 1F. The 7000 Series can measure these values with good accuracy, usually better than required since these standards are less stable than lower valued ones.

Table 1: 7400/7600 Measurement Parameters

Parameter	Measurement Range	Basic Measurement Accuracy*		
		Speed		
		Fast	Medium	Slow
Cs, Cp	00000.01fF – 9.999999F	±0.5%	±0.25%	±0.05%
Ls, Lp	0000.001nH – 99.99999H	±0.5%	±0.25%	±0.05%
D	.0000001 – 99.99999	±0.005	±0.0025	±0.0005
Q	.0000001 – 999999.9	±0.005	±0.0025	±0.0005
$|Z|$, Rs, Rp, ESR, Xs	000.0001mΩ - 99.99999MΩ	±0.5%	±0.25%	±0.05%
$|Y|$, Gp, BP	00000.01µS – 9.999999MS	±0.5%	±0.25%	±0.05%
θ (Phase Angle)	-180.0000 – +179.9999°	±1.8°	±0.9°	±0.18°

* At optimum test signal levels, frequencies, DUT values and without calibration uncertainty.

Mid- & Low-value Capacitance Measurements with the Model 7000 Series

There are some manual precision bridges that can measure capacitance values of 1uF or less with accuracy equal to or better than the Model 7000 Series. Thus the Model 7000 Series is not necessarily recommended for inter-comparison of reference standards in high-level laboratories. The Model 7000 Series is however more than adequate for calibrating the reference standards of lower-level labs and all production capacitance standards and capacitance decade boxes.

Generally, the 7000 Series is more sensitive than manual precision bridges for measurement of 1uF or higher values of capacitance at low frequencies. When measuring lower values of capacitance, its performance is more than acceptable for all but the most stringent requirements. For example, the repeatability when measuring a 1000pF capacitor with the Model 7000 Series at 1kHz is good. The standard deviation is approximately $2\text{ppm}/\sqrt{N}$. N being the number of measurements averaged. So comparisons between standards are quite good. The accuracy is less at lower values, so if possible, lower values should be compared at a higher frequency. At 10kHz one can compare a 100pF standard to better than 1ppm on the Model 7000 Series or a 10pF standard to better than 10ppm. Furthermore, the 7000 Series also offers 4-terminal connection capability, which eliminates connection errors, particularly those due to series inductance at higher frequencies.

In general the overall repeatability of the 7000 Series is comparable to that of the more expensive precision manual bridges if averaging is employed. An automatic instrument is not necessarily less precise than a manual one. They both use the same laws of physics and the automatic instrument has the advantage being able to quickly perform statistical data manipulation.

The Model 7000 Series AutoAcc™ (Automatic Accuracy Calculation) displays the meter uncertainty directly on the front LCD panel without tedious equation solving and table look-up. Most LCR meters require the user to determine the accuracy of an instrument under specific measurement conditions through long tedious and error prone calculations. The Model 7000 Series instruments internal computer performs the required calculations. The user selects the AutoAcc screen, connects the DUT and pushes the START button. The instrument then calculates the accuracy under the set test conditions.

The AutoAcc™ function:

- Easily displays accuracy uncertainties for calibration certificate documentation.
- Optimizes measurement accuracy
- Improves measurement confidence and efficiency
- Eliminates complex manual calculations
- Improves measurement integrity

AC Resistance Measurements with the Model 7000 Series

The QuadTech 7000 Series is unequaled for AC resistance measurements over its frequency range (10Hz to 2MHz). Unfortunately many precision resistance measurements call for DC instead of AC, even though AC measurements avoid thermal voltage errors, have lower noise and can use precise transformer-ratio scaling techniques. Moreover, the size of the unit of resistance (Ω) is determined from AC measurements and has to jump from AC to DC. Attempts have been made to use AC for the most precise resistance measurements, but the DC habit has been hard to break.

For most resistors, the AC-DC difference is negligible at 100Hz or even 1kHz. For flat-card wire-wound resistors, the difference can be less than 1ppm up to 1MΩ if equivalent parallel resistance is used at high values to avoid errors due to lumped parallel capacitance and series resistance is used at low values to avoid errors due to series inductance. Lower measurement frequencies should also be used for very low values to avoid skin effect errors. There are significant differences for high-value, coil-wound resistors, because of capacitance not inductance, and for high-value, multi-resistor networks such as decade boxes and build-up standards. The AC-DC difference of resistance standards are generally very small and often can be easily determined by measuring it, and a small metal film resistor of similar value at both AC and DC. Here the assumption is made that the film unit has negligible AC-DC difference (which it probably does) and that it was stable for the time required (which it usually will be if one doesn't heat it up by applying too much power or touching it). Once such differences are determined, AC could be used for precision calibrations.

Summary

The QuadTech Model 7000 Series Precision LCR Meter should seriously be considered for use in calibration and standards laboratories. It can make many calibrations more accurately than is possible with traditional instruments and it will make other measurements easier and faster. In lower-level labs it can be use for almost all LCR measurements when AC resistance measurements are acceptable.

For complete product specifications on the 7000 Series Precision LCR meters or any of QuadTech's products, visit us at http://www.quadtech.com/resources/dataindex.html. Do you have an application specific testing need? Call us at 1-800-253-1230 or email engineering at rroetzer@quadtech.com and we'll work with you on a custom solution. Put QuadTech to the test because we're committed to solving your testing requirements.

Telephone: 1- 800-253-1230, Website: **http://www.quadtech.com**

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