Lab Manual

IMPEDANCE MEASUREMENT OF THE PIEZOELECTRIC TRANSDUCER

Wayne Kerr LCR Meter 4235

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- **DESCRIBE**
  This manual guides you measure impedance of the piezoelectric transducer.

- **PURPOSE**
  - Prepare the LCR meter 4235 for measurement.
  - Measure capacitance, impedance and phase Angle of the piezoelectric transducer.
  - Calculate the power of the piezoelectric transducer at each frequency.
  - Understanding the piezoelectric transducer

- **MAIN FLOW CHART**
A. **Equipment**

To perform all of the steps in this example, you must have the following equipment:

- LCR meter 4235 (1 unit)
- DUT: The piezoelectric transducer (1 piece)

![DUT](image)

*Figure A.1: DUT*

B. **Preparing (Preparing for a Measurement)**

**Step 1: AC Line Connections**

The unit is provided with a power cable capable of carrying the input current for both 115V and 230V operation. This cable should be connected via a suitable connector to the local AC power supply. The color code employed is as follows:

<table>
<thead>
<tr>
<th>WIRE</th>
<th>EUROPEAN</th>
<th>N. AMERICAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIVE</td>
<td>BROWN</td>
<td>BLACK</td>
</tr>
<tr>
<td>NEUTRAL</td>
<td>BLUE</td>
<td>WHITE</td>
</tr>
<tr>
<td>GROUND</td>
<td>GREEN/YELLOW</td>
<td>GREEN</td>
</tr>
</tbody>
</table>

The supply voltage setting can be checked by looking through the transparent window on the rear panel next to the power inlet socket.
Step 2: Prepare the piezoelectric transducer
- Take the DUT to the measurement area.

⚠️ WARNING DON’T touch the PZT of the Piezoelectric transducer.

Figure B.2: Don’t touch the PZT
Figure B.3: Hold the piezoelectric transducer correctly.

**Step 3:** Turn ON/OFF the Power

Press the power switch to turn ON the power to the LCR meter 4235.

Figure B.4: Turn ON the power to the LCR meter 4235.
Switching the Instrument ON

With the instrument connected to the correct AC power supply press the POWER switch. The power indicator will light and the instrument will display the mode and settings selected when the instrument was last switched off.

If the display is too bright or too dark, use the CONTRAST control above the power switch to set the contrast level.

Switching the Instrument OFF

The power can be switched OFF at any time without damage to the instrument, but to avoid losing trim and calibration data, the instrument should be switched OFF when it is in a quiescent state rather than when it is running a routine, e.g. trimming, calibration or data entry.

NEVER use a power cable showing any sign of damage. Faulty cables can cause electrical shock.

a. Measurement Parameters

Any of the following parameters can be measured and displayed:

**DC Function**

Resistance (Rdc).

**AC Functions**

Capacitance (C), Inductance (L), Resistance (R), Conductance (G), Susceptance (B), Reactance (X), Dissipation Factor (D), Quality Factor (Q), Impedance (Z), Admittance (Y) and Phase Angle (θ).

The following display formats are available:

**Series or Parallel Equivalent Circuit**

C+R, C+D, C+Q, L+R, L+Q

**Series Equivalent Circuit Only**

X+R, X+D, X+Q

**Parallel Equivalent Circuit Only**

C+G, B+G, B+D, B+Q
Polar Form

Z+Phase Angle, Y+Phase Angle

b. Theory reference

b.1. Abbreviations

<table>
<thead>
<tr>
<th>Letter</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Susceptance (=1/X)</td>
<td>R</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>X</td>
</tr>
<tr>
<td>D</td>
<td>Dissipation factor (tan δ)</td>
<td>Y</td>
</tr>
<tr>
<td>E</td>
<td>Voltage</td>
<td>Z</td>
</tr>
<tr>
<td>G</td>
<td>Conductance (=1/R)</td>
<td>ω</td>
</tr>
<tr>
<td>I</td>
<td>Current</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>Subscript s (s) = series</td>
</tr>
<tr>
<td>Q</td>
<td>Quality (magnification) factor</td>
<td>Subscript p (p) = parallel</td>
</tr>
</tbody>
</table>

b.2. Formulae

\[ Z = \frac{E}{I} \quad \text{(all terms complex)} \]

\[ Y = \frac{1}{E} = \frac{1}{Z} \]

\[ Z_s = R + jX = R + j\omega L = R - j \frac{1}{\omega C} \]

\[ |Z_s| = \sqrt{R^2 + X^2} \]

\[ |Z_p| = \frac{RX}{\sqrt{R^2 + X^2}} \]

\[ Y_p = G + jB = G + j\omega C = G - j \frac{1}{\omega L} \]

\[ |Y_p| = \sqrt{(G^2 + B^2)} \]

\[ |Y_s| = \frac{G}{\sqrt{(G^2 + B^2)}} \]

Where

\[ X_L = \omega L \quad X_C = \frac{1}{\omega C} \quad B_C = \omega C \quad B_L = \frac{1}{\omega L} \]

\[ Q = \frac{\omega L_s}{R_s} = \frac{1}{\omega C_s R_s} \quad \text{(series R, L, C values)} \]

\[ Q = \frac{R_p}{\omega L_p} = \omega C_p R_p \quad \text{(parallel R, L, C values)} \]

\[ D = \frac{G_p}{\omega C_p} = \omega L_p G_p \quad \text{(parallel G, L, C values)} \]

\[ D = \frac{G_s}{\omega C_s} = \omega C_s R_s \quad \text{(series R, L, C values)} \]

**NOTE:** The value \( Q = \frac{1}{D} \) is constant regardless of series/parallel convention.
b.3. Series/Parallel Conversions

\[
R_s = \frac{R_p}{1 + Q^2} \quad R_p = R_s(1 + Q^2) \\
C_s = C_p(1 + D^2) \quad C_p = \frac{C_s}{1 + D^2} \\
L_s = \frac{L_p}{1 + \frac{1}{Q^2}} \quad L_p = L_s\left(1 + \frac{1}{Q^2}\right)
\]

Conversion using the above formulae will be valid only at the test frequency.

b.4. Polar Derivations

\[
R_s = |Z| \cos \theta \quad G_p = |Y| \cos \theta \\
X_s = |Z| \sin \theta \quad B_p = |Y| \sin \theta
\]

Note that, by convention, +ve angle indicates an inductive impedance or capacitive admittance.

If capacitance is measured as inductance, the L value will be –ve.
If inductance is measured as capacitance, the C value will be –ve.

\[
D = \tan \delta \quad \text{where } \delta = (90 - \theta)^0 \quad \text{admittance measurement.} \\
Q = \frac{1}{\tan \delta} \quad \text{where } \delta = (90 - \theta)^0 \quad \text{impedance measurement.}
\]

C. Calibration

Step 1: Set the Drive level to 2Vac
- Using the Navigation Keys, highlight the selected Drive level (Non-Soft Key)
- Using the Data Entry Keypad input the value 2Vac

Step 2: Calibrate Mode
- Using the Soft keys to select CALIBRATE, either from the MAIN MENU, or from a mode which has CALIBRATE as an option (in which case pressing the RETURN soft key will return the analyzer to the original mode). The analyzer will enter CALIBRATE MODE.

![Figure C.1: Calibrate mode](image)
**Step 3:** Select O/C Trim

- Using the Soft keys to select O/C Trim
- Open-circuit the Kelvin clips
- Using the Soft keys to select All freq
- Wait until the analyzer has finished trimming

*Figure C.2:* Open-circuit the Kelvin clips

*Figure C.3:* Open the test Leads
Step 4: Select S/C Trim

- Using the Soft keys to select S/C Trim
- Short-circuit the Kelvin clips
- Using the Soft keys to select All freq
- Wait until the analyzer has finished trimming

Figure C.4: Open circuit trim

Figure C.5: Short-circuit the Kelvin clips
If the instrument is switched OFF during O/C trim or S/C trim, the message shown in Figure C.8 will be displayed when the instrument is next switched ON. **MEASUREMENT MODE** will be reset to the default settings and O/C Trim Error or S/C Trim Error or will be displayed at the top of the screen. These messages will only be cleared by performing the appropriate trim. The instrument can be used with the default settings but it is recommended that O/C trim and/or S/C trim is run for full measurement accuracy.

**Figure C.8: Settings Lost**

Figure C.8 will also be displayed when power is removed during other critical routines, such as calibration and data entry.
c.1. The Soft Keys

The following MEASUREMENT MODE parameters are selectable with the ten soft keys to the right of the display.

<table>
<thead>
<tr>
<th>No.</th>
<th>FUNCTIONS</th>
<th>MEANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Rdc Meas</td>
<td>DC Measurement of resistors. The only measurement options are DC drive level (100mV or 1V), range and speed. For full measurement range use a drive level of 1V which corresponds to 10mA max or 2.5mW max in the DUT.</td>
</tr>
<tr>
<td>02</td>
<td>AC Meas</td>
<td>Allows AC measurements to be performed at the selected drive level and frequency. The measurement terms and equivalent circuit are set with the next three soft keys.</td>
</tr>
<tr>
<td>03</td>
<td>C L X B Z Y</td>
<td>The first measurement term. The select X, the Parallel/Series soft key must first be set to Series. To select B, the Parallel/Series soft key must first be set to Parallel. When either Z or Y are selected, the second measurement term is angle (°). The Q D R G and Parallel/Series soft key are not appropriate and are there not shown.</td>
</tr>
<tr>
<td>04</td>
<td>Q D R G</td>
<td>The second measurement term.</td>
</tr>
</tbody>
</table>
To select **G**, the **Parallel/Series** soft key must first be set to **Parallel**.

**05 Parallel/Series**

**Parallel** or **Series** equivalent circuit. All first and second measurement terms are shown above this soft key but only the appropriate measurement terms can be set depending on whether **Parallel** or **Series** is selected. See the narrative on **C L X B Z Y** and **Q D R G** (above) for details.

**06 Show/Hide Scale**

Toggles between **Show Scale** and **Hide Scale**. The selection either shows a diagram of the equivalent circuit, i.e. **Parallel** or **Series**, or shows a bar graph representation of either of the measurement terms (selectable by setting the nominal and limits, see **Abs %** below). The bar graph scale can either be used as a quick visual verification that the component is within the limits set, or can be used for adjustment of variable components. When the measurement falls within the center band the analyzer reports **PASS**

**Notes:**

1) The center portion of the scale length is proportional to the measured value, but scale compression is used above and below the center band.

2) If the binning option is fitted, an external output is available to indicate **PASS** or **FAIL**

**07 Abs %**

Only available when the bar graph scale is displayed. Toggles between **Abs** and **%**. When **Abs** is selected, absolute Hi and Lo limits (i.e. units of the measured parameter) are displayed. When **%** is selected a nominal value together with Hi and Lo percentage limits are displayed.

The limits and nominal value (if applicable) must be set using the and navigation keys to highlight each parameter and the data entry keypad to set each value (the use of the data entry). When in **%** mode, the bar graph scale Hi and Lo limits can easily be set equidistant about the nominal by setting either of the limits then highlighting the other limit and pressing the keypad **Enter** key twice. This mimics the setting of the other limit but with the opposite sign.

**08 Save Nom**

Only available when the bar graph scale is displayed and **%** limits is selected. If a standard component exists, it can be connected to the test leads or fixture
Impedance measurement of the PZT transducer

and measured by the analyzer. Pressing **Save Nom** enters the most recent analyzer measurement of the component as the nominal test value for comparing all subsequent components with.

**Notes:**

1) To change this function from the first to the second measured parameter (or vice versa), first enter a dummy value with units via the keypad; e.g. to change from L to R, enter [1] [unit] [Ω] [Enter] then press the **Save Nom** key.

2) Do not use the **Save Nom** function if the measured value is negative (e.g. an inductor measured above its self-resonant frequency).

**09 Show/Hide Setup**

Once the measurement parameters have been set, **Hide Setup** can be selected to clear them from the screen. The parameter settings are still valid and will be used for component measurements. The bar graph scale and limits will still be displayed. **Hide Setup** is used primarily to unclutter the display, making it more easily readable. Selecting **Show Setup** will redisplay the parameter settings.

**10 CALIBRATE**

Enters **CALIBRATE MODE** which is used for Trimming and Self Calibration.

c.2. **Non-Soft Key MEASUREMENT MODE Parameters**

![Non-Soft Key MEASUREMENT MODE Parameters](image)

*Figure C.10: Non-Soft Key MEASUREMENT MODE Parameters*
c.3. The Navigation Keys

![Navigation Keys Image]

*Figure C.11: The Navigation Keys*

When the set up details are showing on the screen, the left and right navigation keys, and, allow each parameter to be selected in turn.

c.4. The Control Entry Keypad

![Data Entry Keypad Image]

*Figure C.12: The Data Entry Keypad*

The data-entry keypad is a multi-function key set permitting manual entry of data values, measurement units and control codes.

The **Units** key must be used prior to keying a unit or multiplier. Where more than one unit is available on a key, e.g. D/Q or V/A, pressing the key will display the first unit, pressing the key again will display the second unit. Terminate the units mode with **Enter** to accept the key sequence. Pressing **Clear** will delete the whole key sequence; pressing **(the navigation keys)** will delete the last key press.

An invalid keypad entry will cause the entry line to be cleared and an error message, such as the one shown in Figure C.11, to be displayed. The existing settings will be preserved.

![Units mismatched]

*Figure C.13: Example of an Error Message from an Invalid Keypad Entry*

The +/- key may be used before or after a value to change its sign. If the key is pressed more than once, the value will toggle between + and -. For numbers which are positive only, this key is disabled.
**Example 1:** Set the Drive level to 2Vac

- Using the and keys, highlight the selected **Drive level**
- Key the following sequence:
  
  ![Image](image1.png)

  *Figure C.14: Highlight the selected drive level*

**Example 2:** Set the frequency to 14kHz

- Using the and keys, highlight the selected **Measurement frequency**
- Key the following sequence:
  
  ![Image](image2.png)

  *Figure C.15: Highlight the selected frequency*
c.5. Trim Options

Figure C.16: Trim Options

**All freq** trims at a number of frequencies, including the frequency set when the trim was initiated. For most measurements made using standard test leads and fixtures this is the normal trim option to use. The other trim options are normally only used in exceptional circumstances, such as when a special test fixture fails O/C or S/C trim at certain frequencies outside of the component test parameters.

Spot trim trims only at the frequency set in MEASUREMENT MODE.

- <= 10kHz trims at a number of frequencies up to and including 10kHz.
- <= 100kHz trims at a number of frequencies up to and including 100kHz.
- **Abort** cancels the trim and displays the CALIBRATE MODE main screen.

**NOTE**

If, after trimming with an option other than **All freq**, a measurement frequency is selected which is outside of the trim parameters, **O/C Trim Error** or **S/C Trim Error** or will be displayed at the top of the screen and no trim corrections will be applied for the frequency selected. The analyzer can be used without trim correction but full measurement accuracy will not be available until the analyzer is retrimmed using an option which covers the new measurement frequency.
D. **Measurement**

**Step 1:** Connect the DUT

- After performing open and short compensations, the DUT is connected into the Kelvin clips.

![Figure D.1: The DUT connection of the Kelvin clips](image)

**Step 3:** Select **MEASURE**

- Using the **Soft keys** to select **MEASURE**
- **MEASUREMENT MODE** will be displayed

![Figure D.2: The DUT connection of the Kelvin clips](image)
Step 4: Select the parameters

- Use the **Soft keys** to select the following parameters. Pressing the **Soft keys** will either toggle between two options or, where more than two options are available, scroll through the options from left to right, one option at a time.
  
  **AC Meas**
  **C**
  **Q**
  **Series**
  **Show Scale**

- Using the **Navigation keys**, highlight and set each of the following parameters in turn. Settings may be altered one step at a time, or continuously by holding the **Navigation keys** down.
  
  2.00 Vac
  14.800kHz
  Range Auto
  Speed Med

Step 5: Measuring the capacitance

- The screen will display the measured values of **C** and **Q**

![Image of LCR meter](image-url)

*Figure D.3: Measuring the capacitance*
**Step 6**: Measuring the impedance

- Use the **Soft keys** to change the **C** parameter to **Z** parameter
- The screen will display the measured values of **Z** and **Angle**

![Image of LCR Meter](image)

*Figure D.4: Measuring the capacitance*

**E. Analysis (Results of Analysis)**

**Step 1**: Change the frequency

**Step 2**: Measure capacitance

**Step 3**: Measure impedance and Angle

**Step 4**: Calculate the Power

---

NOTE: Perform Step 1 to Step 2 and repeat until fill the below table

<table>
<thead>
<tr>
<th>No.</th>
<th>Frequency (kHz)</th>
<th>Capacitance (nF)</th>
<th>Impedance (kΩ)</th>
<th>Angle (°)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-1</td>
<td>39.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step 5**: Create a 2-D line plot of the Data (X – Frequency; Y – Impedance)

**Step 6**: Compare with frequency of piezoelectric transducer

- Compare your results with the Figure E.1
**Piezoelectric Impedance**

The electrical impedance is a distinguishing characteristic for piezoelectric elements. It differs substantially from the impedance of non-piezoelectric dielectric elements when driven at high-enough frequencies. The difference stems from the coupling of electrical energy input to mechanical motion output.

Recall that the electrical impedance is defined as the voltage drop across an element divided by the current through the element. For a (simple geometry) piezoelectric element, the electrical impedance over a given frequency range will appear similar to that shown here:

The impedance for a non-piezoelectric element (of the same shape and dielectrical properties) is also shown in blue.

The presence of electrical resonances and anti-resonances make the piezoelectric impedance unique. The resonances result from the electrical input signal exciting a mechanical resonance in the piezo element. For each mechanical resonance in the piezo element, a resonance/anti-resonance pair will exist in the impedance.
e.1. Piezoelectric Transducer Working Principle:

Piezoelectric Transducer Working Principle – A symmetrical crystalline materials such as Quartz, Rochelle salt and Barium titanate produce an emf (electromotive force) when they are placed under stress. This property is used in Piezoelectric transducer working principle, where a crystal is placed between a solid base and the force-summing member as shown in Figure E.2.

![Figure E.2: Piezo Electric Transducer](image)

An externally applied force, entering the transducer through its pressure port, applies pressure to the top of a crystal. This produces an emf across the crystal proportional to the magnitude of applied pressure.

The following electric circuit can be used to model a resonance/anti-resonance pair the electrical impedance of piezoelectric.

The following 2 conditions are required for the circuit to accurately simulate piezoelectric resonance behavior:

- The value of C must be much smaller than $C_p$
- $C_1$ and $C_p$ in parallel must equal the piezo’s low-frequency capacitance

The frequencies (in Hz) of the electrical resonance and anti-resonance are given by the following equations (which assume as small series resistance $R$):

$$f_{\text{resonance}} = \frac{1}{2\pi \sqrt{L_1 C_1}}$$

$$f_{\text{anti-resonance}} = \frac{1}{2\pi \sqrt{L_1 \frac{C_1 C_p}{C_1 + C_p}}}$$
e.2. RLC Circuits

**AC emf source:** “Driving frequency” $f$

$\varepsilon = \varepsilon_m \sin \omega t$ \hspace{1cm} $\omega = 2\pi f$

**Current:**

$i = I_m \sin(\omega t - \theta)$ \hspace{1cm} $I_m = \frac{\varepsilon_m}{Z}$

**Inductive reactance**

$X_L = \omega L$

**Capacitive reactance**

$X_C = \frac{1}{\omega C}$

**Total impedance**

$Z = \sqrt{R^2 + (X_L - X_C)^2}$

$Z$ is minimum when $X_C = \frac{1}{\omega C}$ \hspace{1cm} $\omega = \omega_0 = \frac{1}{\omega C}$

$\Rightarrow$ This is resonance

At resonance:

- Impedance = $Z$ is minimum
- Current amplitude = $I_m$ is maximum

**Pictorial Understanding of Reactance**

\[
\tan \theta = \frac{\omega L - \frac{1}{\omega C}}{R} \equiv \frac{X_L - X_C}{R}
\]

\[
\cos \theta = \frac{R}{Z}
\]

**Power in AC Circuits**

$P_{ave} = \frac{\varepsilon_{rms}^2}{Z} \cos \theta$

$\cos \theta$ is the “power factor”

- To maximize power delivered to circuit $\Rightarrow$ make $\theta$ close to zero
- Max power delivered to load happens at resonance