Inductive Electrical Conductivity Measurement From Tayos Corp
(User Guide – August 22, 2022)

Introduction to the Model TC-X1:

The TC-X1 is designed around the Texas Instruments LDC1101 inductance to digital converter (see link in ref. section) and relies on methods recently published in the literature (IEEE Sensors Journal, Vol. 21, No. 1, January 2021 – link below). These new findings permit a quantitative calculation of electrical conductivity for non-magnetic specimens when placed into non-conductive cylindrical vessels that are centered directly above a short solenoidal coil. Unlike existing conductivity instrumentation, no electrodes or immersive probes are needed. Instead, conductivity measurements are based on the induction of eddy currents, as described in the IEEE Sensors journal article.

When standard petri dish vessels, filled to standard depth, are used to contain the desired specimen, no calibration is required to accurately measure electrical conductivity as small as ~0.50 mS/cm, with 1% accuracy. Use of larger vessels would allow measurement of smaller conductivities, i.e. greater sensitivity. The filled petri dish is simply centered on the induction coil and conductivity is read from the liquid crystal display, or LCD. If conductivity is expected to exceed ~1000 mS/cm, calibration in that higher range may be needed. In some cases, it may be necessary to desensitize the response of the instrument, which may be achieved by placing the sample farther away from the sensor. This may be accomplished using non conductive spacers, such as EVA foam. Using a shallower fill of the petri dish will also reduce sensitivity.

If non-standard sample holders are used, calibration may also be required using standards of your choice. Alternatively, the calibration constant that links inductive loss with electrical conductivity can be computed or measured – for example, if the cylindrical specimen holder radius has been changed (see section on calibration).

Because of the noninvasive nature of the TC-X1, a wide variety of materials can be measured that would be challenging or even impossible to accommodate with conventional instruments based upon conductivity cells using delicate platinum coated electrodes or any kind of probe that requires insertion into the sample. Some examples of materials or systems that fit this criteria include:

a. Various solids (formed into a short cylinder)
b. Rock cores – cylindrical shape
c. Granular materials mixed with conductive liquids
d. Slurries
e. Pastes
f. Paints
g. Toxic wastes
h. Emulsions
i. Biological cultures & media
j. Soils in various degrees of saturation
k. Various mixtures of strong acids or strong bases
l. Concentrated solutions of electrolytes of unknown composition
m. Foods (in non-conductive container)
n. Wet cement pastes, in various states of cure
o. Sewage sludges
p. Animal excrement
q. Solid salt solutions

Calibration of the TC-X1(if needed):

When using a standard 10 cm petri dish, filled to standard depth, no calibration is needed. Even if filled to a shallower depth, simple commands can be sent to the unit over BT serial to specify the correct, user-assigned filling depth or specimen height above the stage (a different container may impose a larger or smaller coil-specimen gap height). As always, non-standard containers can be accommodated by appropriate calibration with standard KCl(aq) solutions placed into any cylindrical container.

If a standard specimen cell cannot be used, or adjustment made for specimen height or coil-specimen gap, calibration is required, using appropriate standards, such as aqueous potassium chloride (KCl). Ordinarily, a user will have a particular specimen container in mind. This container should be used to calibrate the instrument.

Likely, a conductivity range is expected for a set of unknowns. Thus, a set of standards should be prepared that encompasses the expected range and uses the same container style as planned for the unknowns. Typical conductivity standards are salt solutions and can be made up in the desired specimen containers. If this is not practical, a computed calibration curve can be generated from the container's dimensions and sample height, using theory described in the IEEE reference – this calibration can be provided to the user, as a service from Tayos.

The TC-X1 firmware is currently set up for maximum sensitivity. This means that conductivity exceeding ~350 mS/cm may not register correctly in the LCD window when used under standard conditions. To handle this situation, the instrument is easily rendered less sensitive to the sample by either increasing the coil-specimen gap or reducing the amount of fill in the petri dish. Both of these methods may be used in the event that a specimen has an unusually large conductivity. In this way, very high specimen conductivity may be accommodated.

Commands & Data Over BT Serial:

BlueTooth (BT) is usually available on most platforms and can be useful for communicating with the TC-X1. Commands can be sent to the TC-X1 to make small modifications to calibration, or stream data to the laptop. The pairing code for the TC-X1 is: SCMIT (all uppercase letters). The unit name is printed on the unit's underside. BAUD rate must be set at 38,400 to work properly with the TC-X1. Use defaults for all other serial port parameters.

If not using custom software, the Arduino IDE and interface can be downloaded from: https://www.arduino.cc/en/software , for free. Once downloaded and set up on your computer, the IDE can be launched, giving access to either the Serial Monitor or Serial Plotter, under the Tools dropdown. When using either serial tool, both conductivity (mS/cm) and LDC1101 frequency (MHz) are provided. The Serial Plotter tool is especially useful when conductivity changes are expected to occur rather quickly, which then allows data changes to be more easily visualized.

BT (bluetooth) Commands (API):

The following commands can be sent via Arduino IDE serial tools or custom software, **after issuing the command "~TC" (without quotes) to force a pause**:–

1. ~NCijk : specify the number of integer LDC1101 conversions per acquired conductivity value; 001 < ijk < 999; this is 060, or 60 conversions by default. To stream ~1 sample per second, use ~850 conversions per sample; results in the LCD will then appear every ~10 seconds.
2. ~SLx : specify a non-default coil inductance, where x is float type; this is set to 2.15 **μ**H by default – should only be used with help from Tayos.
3. ~BV : returns the current battery voltage – this is routinely checked so that the response "Lo_Batt:" appears in the LCD window if voltage is less than 3.60 volts DC.
4. ~VR : returns the current firmware version in the microcontroller; a newer version can be uploaded, via the micro USB plug on the left side of the unit; the correct board, when loaded via the Arduino IDE is the Adafruit 32u4.
5. ~TC : returns the current temperature inside the TC-X1 box, in degrees Celsius; temperature is important, inasmuch as intrinsic loss in a copper coil is temperature dependent; this need not be a concern though, since the tare button is used to subtract out this small contribution to loss / conductivity.
6. ~RGy : this command allows the user to specify a non default gap, float y, in cm, between the induction coil and the specimen. If using standard containers, the default value is 0.1 cm. (allowed: 0.0 cm up to 0.25 cm)
7. ~RHz : this command allows the user to specify a non default specimen height, or thickness, float z, in cm. If using standard containers, the default value is 1.0 cm. (allowed: 0.5 cm up to 3.0 cm)

Note that after entering a new number of desired conversions, via the ~NC command, the unit will simply reenter "L-mode", and begin providing conductivity measurements until some other command is entered. "L-mode" is the default mode and is entered when the unit is first powered on. A quick way to return to default settings is to switch off and then repower the instrument.

Currently, the lookup table supports coil-specimen gaps ranging from 0.0 cm up to 0.25 cm, and specimen thicknesses from 0.5 cm up to 3.0 cm. Future firmware versions may expand these ranges and accommodate other sample holders with other radii, as needed by practitioners. If outside these ranges, lab calibration is required for accurate results. When working within these ranges, the correct conductivity will appear in the LCD display window.

<u>Usual Measurement Practice</u>:

The unit should never be used while recharging the Li-ion polymer battery. This is partly due to the ripple that is usually present on most charging supplies. In addition, stray capacitance effects are likely to occur between the coil and nearby cables and devices connected to those cables. Once a sample has been placed onto the sensor, the sample holder should not be touched as this will add unwanted capacitance effects that alter readings.

Once the battery has been fully charged, and cable removed, the unit is ready to measure electrical conductivity. **Please note that charging only takes place when the power switch is placed in the ON position**. A standard 10 cm diameter petri dish, filled to a depth of 1.0 cm, is placed onto the stage – centered on the coil – and once readings have stabilized, conductivity may be read in units of mS/cm. If the specimen is a non viscous fluid, the empty dish may be first put in place and thereafter filled with specimen to a depth of 1.0 cm.

If placing a nearly empty dish on the coil stage shows some small amount of conductivity, this may be zeroed out using the tare button prior to completely filling the dish. Furthermore, if over time, drift begins to accrue, the tare button may be pushed to rezero the unit.

Brief Theory of Operation:

The TC-X1 is based upon the Texas Instruments chip LDC1101, which works with the induction coil to form a tank circuit that oscillates at ~ 8 MHz. Proprietary circuitry within the LDC1101 is able to measure the loss within the tank circuit due to the formation of eddy currents in an electrically conductive, non-magnetic specimen. Data from the LDC1101 is acquired over a standard SPI line using a basic ATmega32u4 processor from Microchip, as implemented by Adafruit on their proto board. Tayos Corp wrote the proprietary library needed to interface the LDC1101 with the ATmega32u4.

For conductivity less than about 1000.0 mS/cm, a quantitative formula is available that connects inductive loss with electrical conductivity (see the IEEE ref.). Larger conductivities may require calibration if linearity ceases to be observed. Otherwise, the TC-X1 uses the results of that quantitative result to build the look-up table that is included in TC-X1 firmware. When inductive loss is very small, the LDC1101 has difficulty measuring conductivity beneath ~0.1 mS/cm – this is currently expected to be the lower limit of the instrument. However, use of larger sample size can extend the lower limit of measurement with the eddy current method.

Because no inductor is ideal, there are features associated with inductive sensing that a user should be aware of in order to yield the best results. As is true with any inductor, the metallic windings of the short solenoid used in the TC-X1 will behave as a capacitor – includes capacitance between windings, but more importantly, the capacitance arising between metallic coil windings and the nearby environment. The latter capacitance can have losses associated with it that interfere with the measurement of the intended inductive loss. To obtain the best results, metallic objects should be kept as far away as is practical from the TC-X1. Furthermore, readings should not be made while the unit is charging, since this effectively places the charging cable and anything the cable is attached to into electrical contact with the unit, even if only capacitively. As a general rule, isolation is the best strategy.

References:

1. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9154723
2. https://www.ti.com/product/LDC1101

PRODUCT DISCLAIMER

Tayos will not be held accountable for damages to the product or instrument, occurring due to misuse or mishandling by the user. User assumes full responsibility for any product use or practice outside of recommended practices. User also assumes responsibility for any conclusions that the user makes as a result of measurements made with the instrument.