ANALOG DEVICES

Circuit Note
CN-0346

Circuits from the Lab® Reference Designs

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| Devices Connected/Referenced | |
|---|---|
| AD7745 | 24-Bit Capacitance-to-Digital Converter with Temperature Sensor |
| AD8615 | Precision Rail-to-Rail Input/Output CMOS Op Amp |

# Relative Humidity Measurement System

## EVALUATION AND DESIGN SUPPORT

**Circuit Evaluation Boards**

- **CN-0346 Circuit Evaluation Board (EVAL-CN0346-PMDZ)**
- **SDP-I-PMOD Interposer Board (SDP-PMD-IB1Z)**
- **System Demonstration Platform, SDP-B (EVAL-SDP-CB1Z)**

**Design and Integration Files**

- **Schematics, Layout Files, Bill of Materials**

## CIRCUIT FUNCTION AND BENEFITS

The two-chip circuit shown in Figure 1 provides a contactless, capacitive based, relative humidity (RH) measurement solution with 2% relative humidity accuracy from 0% RH to 100% RH, and replaces bulky hygrometer based methods. The circuit is ideal for applications where accurate, temperature controlled, noncontact humidity measurements are critical, such as HVAC, telecommunication cabinets, infant incubators, and other industrial or medical applications.

Moisture causes the dielectric constant of a capacitive sensor to change with respect to the relative humidity of the surrounding environment. For example, the Innovative Sensor Technology P14-W capacitive sensor used in this circuit is comprised of a top electrode, polyimide layer and a bottom electrode, and has a sensitivity of (0.25 pF/% RH) and a linearity of 1.5% RH.

The humidity sensor output is digitized by the AD7745, 24-bit, Σ-Δ capacitance-to-digital converter (CDC). A 2-wire, $I^2C$-compatible interface allows access to the internal configuration registers as well as to the data conversions.

The AD8615 rail-to-rail amplifier with very low offset voltage (65 µV) and wide signal bandwidth (>20 MHz) acts as a unity-gain buffer and provides the appropriate drive signal to the sensor.

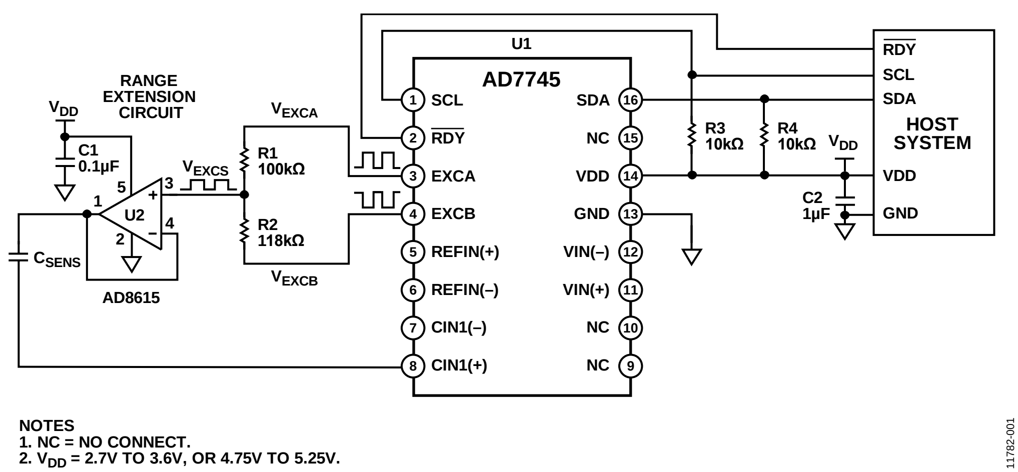


*Figure 1. Capacitive Sensing Based Humidity Measurement System (Simplified Schematic: Decoupling and All Connections Not Shown)*



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## CIRCUIT DESCRIPTION

RH is the amount of water vapor in the air, expressed as a percentage of the maximum amount that the air can hold at a specific temperature. Relative humidity is an important metric because it takes into consideration the effects of temperature and pressure.

A hygrometer is the traditional device used to measure RH and has taken many forms over time, including metal paper coil, human hair, and dual thermometer implementations. Modern day electronic implementations use a capacitive element that is robust against aging effects, condensation, and rapid temperature swings.

Capacitive sensors experience a change in their dielectric constant when a polymer or metal oxide layer is subject to varying amounts of moisture. Most capacitive sensors require several seconds to respond to a change in humidity.

### *Humidity Sensor Characteristics*

The circuit shown in Figure 1 uses the Innovative Sensor Technology P14-W series of capacitive sensors. Bulk capacitance, sensitivity, temperature, linearity, and hysteresis are the important specifications of the sensor.

The typical bulk capacitance of the sensor is 150 pF ± 50 pF at 30% RH. This common-mode capacitance does not influence the relative humidity reading but requires a special circuit to interface to the capacitance-to-digital converter.

The sensitivity of the capacitive element determines the relative humidity reading. Sensitivity is the change in capacitance for a 1% change in relative humidity and is calculated by measuring the capacitance at two unique relative humidity points and dividing by the change in percent RH.

$$Sensitivity = \Delta C/\Delta\%\ RH$$

The P14-W has a typical sensitivity of 0.25 pF/% RH.

$$Sensitivity = \frac{C_{95\%RH} - C_{10\%RH}}{90\% - 15\%}$$

Calculate the temperature dependence of the sensor for a particular relative humidity condition using the following equation and coefficients (taken from the Innovative Sensor Technology P14-W data sheet):

$$T_{DEPEND} = (B1 \times \%\ RH + B2) \times T\ [°C] + (B3 \times \%\ RH + B4)$$

where:
$B1$ = 0.0014/°C
$\%\ RH$ = 42%
$B2$ = 0.1325% RH/°C
$T$ = 23°C
$B3$ = −0.0317
$B4$ = −3.0876% RH

$T_{DEPEND}$ = −0.0191% RH.

A temperature of 23°C causes a change in a 42% RH calculation of −0.0191% RH. Adding this value to the calculated % RH corrects for the temperature dependence of the sensor.

The linearity and hysteresis of the Innovative Sensor Technology P14-W series are ±1.5% RH.

### *Calculating Relative Humidity*

Relative humidity is calculated from the capacitance, C, and temperature, T, readings as follows:

1. Subtract the bulk capacitance from the capacitance reading.
2. Divide by the sensitivity.
3. Add the reference humidity to the calculation.
4. Calculate the temperature dependence, $T_{DEPEND}$.
5. Add $T_{DEPEND}$ to the result in Step 3.

As an example, assume a capacitive sensor reading of C = 153 pF at a temperature of T = 23°C, with the following ideal characteristics:

- Bulk capacitance = 150 pF at 30% RH
- $T_{DEPEND}$ = −0.0191% RH
- Sensitivity = 0.25 pF/% RH
- Reference point = 30% RH, 23°C

Calculate the relative humidity according to the instructions given and the following equation:

$$RH = RH_{REF} + \left(\frac{C - C_{BULK}}{Sensitivity}\right) + T_{DEPEND}$$

$$RH = 30\%\ \text{RH} + \left(\frac{153\ \text{pF} - 150\ \text{pF}}{0.25\ \text{pF}/\%RH}\right) - 0.0191\%\ \text{RH}$$

$$RH = 30\%\ \text{RH} + 12\%\ \text{RH} - 0.0191\%\ \text{RH}$$

$$RH = 41.809\%\ \text{RH}$$

The method for calculating the temperature dependence of the relative humidity measurement is dependent upon the particular humidity sensor selected; therefore, the data sheet must always be consulted to determine the correct formula.

### *Capacitance-to-Digital Converter (CDC)*

The 24-bit AD7745 CDC measures capacitance by using a switched capacitor charge balancing circuit, as shown in Figure 2. The throughput rate is 10 Hz to 90 Hz.

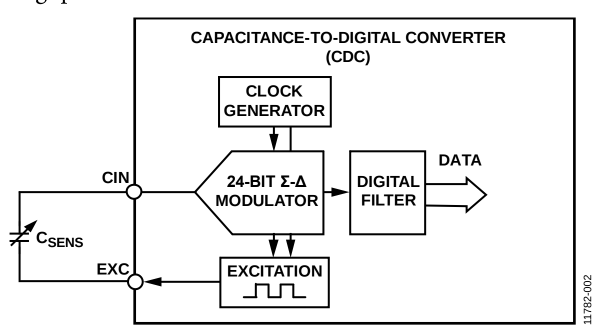


*Figure 2. Single-Ended Capacitive Sensor Implementation*

Charge is proportional to the product of voltage and capacitance, Q = V × C, and the conversion result represents the ratio of the input sensor capacitance, $C_{SENS}$, to the internal reference capacitance, $C_{REF}$. The excitation voltage (EXC) and the internal reference voltage ($V_{REF}$) have fixed known values.

The $C_{SENS}$ to be measured connects between the excitation source and the Σ-Δ modulator input. A square-wave excitation signal of 32 kHz is applied to $C_{SENS}$ during the conversion, and the modulator continuously samples the charge going through $C_{SENS}$. The digital filter processes the modulator output, which is a stream of ones and zeros. The conversion value is contained in the ones density of the bit stream. The data from the digital filter is scaled, calibration coefficients are applied, and the result is read through the serial interface.

### Input Range Scaling

The AD7745 has two limitations in measuring input capacitance. First, the dynamic range is ±4.096 pF, but many capacitive based humidity sensors have a larger dynamic range. Second, the maximum common-mode capacitance of the CDC is 21 pF. Many humidity sensors have a larger bulk capacitance.

The AD7745 has the ability to offset the input common-mode range by programming the internal, 7-bit, capacitor DAC (CAPDAC) registers. The CAPDAC acts as a negative capacitance connected internally to the CIN1± pin. This allows a common-mode capacitance of up to a typical value of 21 pF.

The range extension circuit shown in Figure 1 is added to ensure that the charge transfer within $C_{SENS}$ remains within the input range of the AD7745. To achieve this, the excitation voltage is decreased by a factor of F, allowing the sensor capacitance to be increased by a factor of F.

### Calculating Range Extension Factor

To calculate the range extension factor, the two independent excitation sources (EXCA and EXCB) of the AD7745 must be programmed such that EXCB is the inverse of EXCA. With Resistors R1 and R2 connected as shown in Figure 1, the resulting range extension factor F is the ratio of the AD7745 differential excitation voltage between EXCA and EXCB ($V_{EXCA}/V_{EXCB}$) and the attenuated excitation signal ($V_{EXCS}$) at the positive input of the AD8515 op amp. Calculate the range extension factor as follows:

$$F = \frac{V_{EXCA}/V_{EXCB}}{V_{EXCS}} = \left|\frac{R1 + R2}{R1 - R2}\right|$$

The average voltage of the attenuated excitation voltage, $V_{EXCS}$, is VDD/2. The AD8515 op amp functions as a low impedance buffer to ensure that $C_{SENS}$ is fully charged when the AD7745 starts sampling.

The sensor bulk capacitance can be as high as 200 pF, and the minimum value of the AD7745 common-mode capacitance is 17 pF, resulting in a required range extension factor ($F_{CM}$) of

$$F_{CM} = 200\text{ pF}/17\text{ pF} = 11.76$$

Calculate the sensor dynamic range as follows:

$$C_{DYN} = (0.25\text{ pF}/\%\text{ RH}) \times 100\%\text{ RH} = 25\text{ pF}$$

Calculate the range extension factor required for the dynamic range ($F_{DYN}$) as follows:

$$F_{DYN} = 25\text{ pF}/8.192\text{ pF} = 3.05$$

These calculations show that the bulk capacitance of the sensor is the parameter that determines the range extension factor; therefore, F = 11.76 is used for further calculations.

### Choosing the Resistor Values

Select values for R1 and R2 to implement the desired range extension factor. A value of 100 kΩ was chosen for R1. The resistor value for R2 is calculated and rounded down to the next value in the standard E96 series.

$$R2 = \frac{R1 \times (F + 1)}{F - 1}$$

where:
$R1$ = 100 kΩ
$F$ = 11.76
$R2$ = 118.58 kΩ.

Use resistors with tolerances of 1% or less. A small change in the value of either resistor (R1 or R2) can significantly change the range extension factor. The resistor values of 100 kΩ for R1 and 118 kΩ for R2 result in a range extension factor of

$$F = \left|\frac{R1 + R2}{R1 - R2}\right| = \left|\frac{100 + 118}{100 - 118}\right| = 12.11$$

### Using the CAPDAC to Remove the Common-Mode Capacitance

The AD7745 capacitive input is factory calibrated so that the input range is 0 pF to 4.096 pF in the single-ended mode, and ±4.096 pF in the differential mode. The AD7745 contains an internal CAPDAC that allows adjustment of the input common-mode capacitance.

The CAPDAC acts as a negative capacitance connected internally to the CIN1± pin. There are two independent CAPDACs, one connected to CIN1(+) and the second connected to CIN1(−).

The CAPDACs have 7-bit resolution and a full-scale value of 21 pF ± 20%.

Calculate the required CAPDAC setting for the single-ended humidity sensing element example shown in Figure 1 by setting the CAPDAC for a common-mode capacitance of 17 pF corresponding to the decimal code value of

$$CAPDAC_{CODE} = \frac{17\text{ pF}}{21\text{ pF}} \times 127 = 103\text{, or 0x67}$$

### *Test Setup*

Gathering test data cannot begin until the CN-0346 system is properly set up and calibrated. First, place the EVAL-CN0346-PMDZ printed circuit board (PCB) into a humidity controlled chamber with access to a precision inductance capacitance resistance (LCR) meter (HP4284A). The LCR meter correlates any capacitance calculation with the actual capacitance value of the sensor. Two sets of wires protrude from the container for each PCB. The first set of wires is specific to $I^2C$ digital communication. The second set of wires allows direct measurement of the sensor capacitance using the LCR meter, which can only occur when there is no power connected to the EVAL-CN0346-PMDZ PCB.

Figure 3 shows the block diagram used for data collection in the bench test setup.

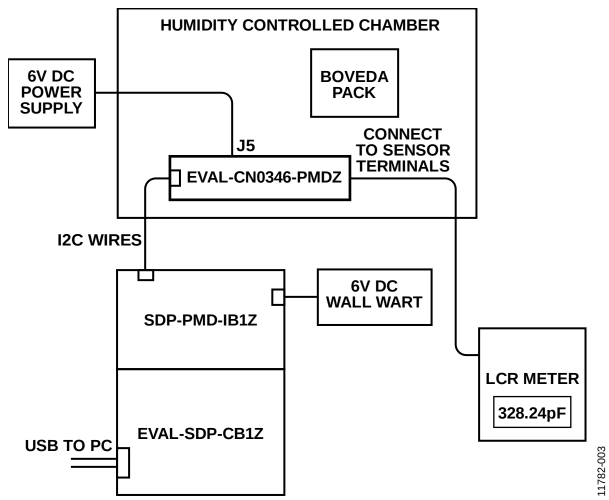


*Figure 3. Bench Test Block Diagram*

Second, for two specific humidity levels (5% RH and 95% RH), measure the temperature of the enclosure using the AD7745 and measure the capacitance of the sensor using the LCR meter. Calculate the sensitivity of the sensor using these two calibration points.

$$Sensitivity = \frac{C_{95\%\,RH} - C_{10\%\,RH}}{95\% - 10\%}$$

Enter the sensitivity into the appropriate **Relative Humidity Calculation** field under the **Calculations** tab (see Figure 4). Use the 10% RH calibration point to fill in the **C_BULK** field and the **RH_REF** (%) field.

Lastly, calculate and input the desired CAPDAC common-mode value into the **CAPDAC** field, as shown in Figure 5.

The CN-0346 system is prepared and calculated. **Click to Sample** displays the sensor capacitance as **C_CALC** in the **Capacitance Calculation** window. Vary the humidity while collecting samples and observe the change in the relative humidity calculation.

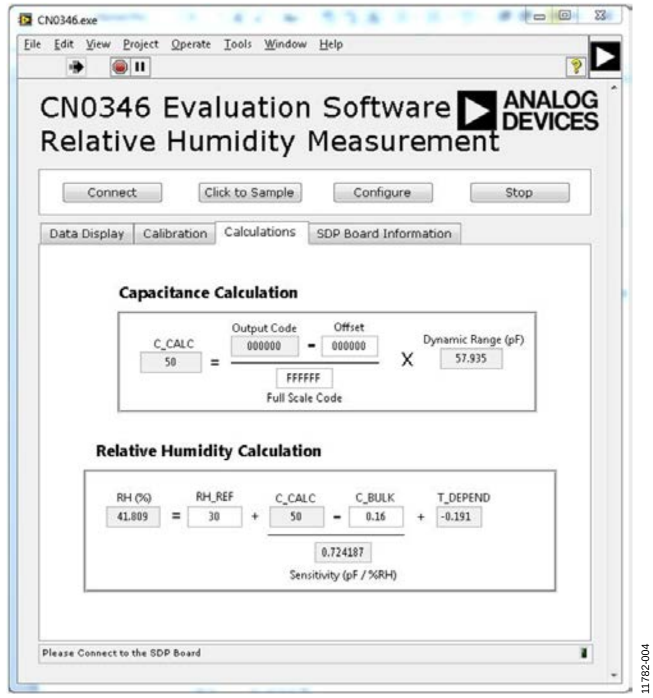


*Figure 4. Screenshot of the CN-0346 Evaluation Software, **Calculations** Tab*

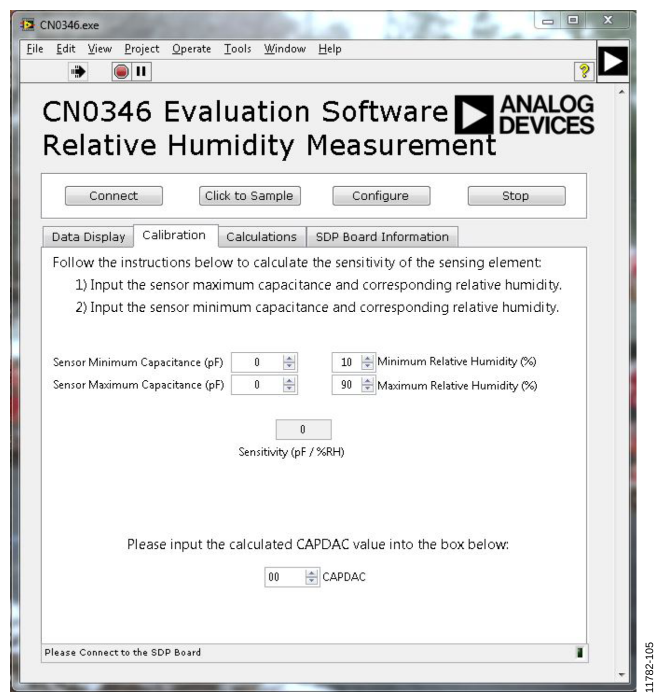


*Figure 5. Screenshot of the CN-0346 Evaluation Software, **Calibration** Tab*

### Test Results

All test data was collected by placing Boveda packs (Boveda, Inc.) into a sealed container with three EVAL-CN0346-PMDZ PCBs, as shown in Figure 6. Boveda packs contain a specially prepared solution of pure water and salt, designed to control the humidity inside of a sealed container to a specific, predetermined relative humidity of ±2.5%.


*Figure 6. Data Collection Bench Test Setup*

Figure 7 shows the relative humidity error over the full range of relative humidity.

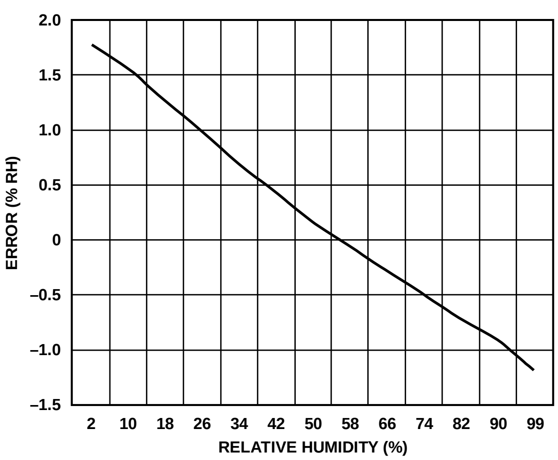


*Figure 7. Relative Humidity Measurement Error*

### PCB Layout Considerations

In any circuit where accuracy is crucial, consider the power supply and ground return layout on the board. The PCB isolates the digital and analog sections as much as possible. The PCB for this system is constructed in a 4-layer stack up with large area ground plane layers and power plane polygons. See the MT-031 Tutorial for more information on layout and grounding, and see the MT-101 Tutorial for information on decoupling techniques.

Decouple the power supply to all ICs with 1 µF and 0.1 µF capacitors to properly suppress noise and reduce ripple. Place the capacitors as close to the device as possible. Ceramic capacitors are recommended for all high frequency decoupling.

Power supply lines must have as large a trace width as possible to provide low impedance paths and to reduce glitch effects on the supply line. Shield clocks and other fast switching digital signals from other parts of the board by connecting them to the digital ground. The PCB is shown in Figure 8.

A complete design support package for this circuit note is available at www.analog.com/CN0346-DesignSupport.

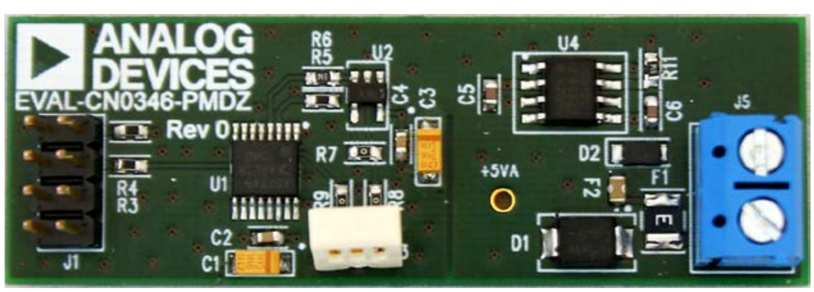


*Figure 8. Photo of the EVAL-CN0346-PMDZ PCB*

## COMMON VARIATIONS

Capacitive sensing can also be used to implement a proximity sensor. A basic proximity sensor includes a receiver and a transmitter, each of which consists of metal traces formed on layers of a PCB. The AD7745 has an on-chip excitation source, which connects to the transmitter trace of the sensor. An electric field is generated between the receiver and the transmitter trace. Most of the field is concentrated between the two layers of the sensor PCB. However, a fringe electric field extends from the transmitter, out of the PCB, and terminates back at the receiver. The field strength at the receiver is measured by the on-chip, Σ-Δ CDC. The electrical environment changes when a human hand invades the fringe field, and a portion of the electric field is shunted to ground instead of terminating at the receiver. The resulting decrease in capacitance (on the order of femtofarads as compared to picofarads for the bulk of the electric field) is detected by the converter.

## CIRCUIT EVALUATION AND TEST

This circuit uses the EVAL-SDP-CB1Z system demonstration platform (SDP) evaluation board and the EVAL-CN0346-PMDZ circuit board. The two boards have 120-pin mating connectors, allowing the quick setup and evaluation of the performance of the circuit.

The EVAL-CN0346-PMDZ contains the circuit to be evaluated, as described in this circuit note. The EVAL-SDP-CB1Z is used with the CN-0346 Evaluation Software to capture the data from the EVAL-CN0346-PMDZ. The SDP/PMD interposer board (SDP-PMD-IB1Z) is used to connect the EVAL-CN0346-PMDZ board to the EVAL-SDP-CB1Z board, as shown in Figure 3.

### *Equipment Needed*

The following equipment is needed:

- The EVAL-CN0346-PMDZ evaluation board
- The EVAL-SDP-CB1Z evaluation board
- The SDP/PMD interposer board (SDP-PMD-IB1Z)
- The CN-0346 Evaluation Software
- A PC with a USB port and Windows® XP, or Windows Vista® (32-bit), or Windows® 7 (32-bit)
- A capacitive humidity sensor, Innovative Sensor Technology P14-W (included on EVAL-CN0346-PMDZ board)
- A 6 V at 100 mA power supply
- A 6 V wall wart
- A humidity controlled chamber

### *Getting Started*

Load the evaluation software by placing the CN-0346 Evaluation Software CD into the PC. Using **My Computer**, locate the drive that contains the evaluation software CD and open the **Readme** file. Follow the instructions contained in the **Readme** file for installing and using the evaluation software.

### *Functional Block Diagram*

See Figure 3 for the test setup block diagram, and the **EVAL-CN0346-SDPZ-SCH-RevX.pdf** file for the circuit schematics. This file is contained in the CN-0346 Design Support Package.

### *Setup*

Connect the 120-pin connector on the EVAL-SDP-CB1Z to the SDP-PMD-IB1Z board. Use nylon hardware to firmly secure the two boards, using the holes provided at the ends of the 120-pin connectors. Connect the EVAL-CN0346-PMDZ to Connector J2 on the SDP-PMD-IB1Z board.

With the power supply off, connect a 6.0 V dc barrel jack to Connector J1 on the SDP-PMD-IB1Z board. Connect the USB cable supplied with the EVAL-SDP-CB1Z to the USB port on the PC. With the power supply off, connect the 6 V power to the J5 connector of the EVAL-CN0346-PMDZ evaluation board. Do not connect the USB cable to the mini USB connector on the SDP board at this time.

Place the entire setup into a sealed chamber with humidity control. It is also possible to place only the sensing element into the environment of interest, if so desired. An external hygrometer or other calibrated humidity sensor can be used as a reference point for calibrating or verifying the output data from the CN-0346 Evaluation Software.

### *Test*

Apply power to the dc barrel jack, Connector J1, of the SDP-PMD-IB1Z board. Apply power to the J5 connector of the EVAL-CN0346-PMDZ board. Launch the CN-0346 Evaluation Software and connect the USB cable from the PC to the mini-USB connector on the EVAL-SDP-CB1Z.

When USB communications are established, the EVAL-SDP-CB1Z can be used to send, receive, and capture serial data from the EVAL-CN0346-PMDZ.

Information regarding the EVAL-SDP-CB1Z can be found in the SDP User Guide. Information and details regarding test setup and calibration, and how to use the evaluation software for data capture can be found in the CN-0346 Software User Guide.

## LEARN MORE

CN0346 Design Support Package: http://www.analog.com/CN0346-DesignSupport

MT-031 Tutorial, *Grounding Data Converters and Solving the Mystery of AGND and DGND*, Analog Devices.

MT-101 Tutorial, *Decoupling Techniques*, Analog Devices.

### *Data Sheets and Evaluation Boards*

CN-0346 Circuit Evaluation Board (EVAL-CN0346-PMDZ)

System Demonstration Platform (EVAL-SDP-CB1Z)

AD7745 Data Sheet

AD8615 Data Sheet

## REVISION HISTORY

**9/14—Revision 0: Initial Version**

I[2]C refers to a communications protocol originally developed by Philips Semiconductors (now NXP Semiconductors).



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