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Devices Connected/Referenced	
AD7745/ AD7746	24-Bit Capacitance-to-Digital Converter
AD8515	1.8 V Low Power CMOS Rail-to-Rail Op Amp

Extending the Capacitive Input Range of the AD7745/AD7746 Capacitance-to-Digital Converter

CIRCUIT FUNCTION AND BENEFITS

This circuit provides a method to extend the capacitive input range of the AD7745/AD7746. How to use the on-chip CapDAC sufficiently in order to minimize the range extension factor and, therefore, optimize the circuit to achieve the best possible performance is also explained. The AD7745 has one capacitance input channel, while the AD7746 has two channels. Each channel can be configured as single-ended or differential.

CIRCUIT DESCRIPTION

The AD7745/AD7746 capacitance-to-digital converters measure capacitance by using switching capacitor technology to build up a charge balancing circuit. As charge is proportional to the product of voltage and capacitance, Q = V × C, the conversion result represents the ratio between the input capacitance, C_{SENS}, and the internal reference capacitance, C_{REF}, as the excitation voltages EXCx and the internal reference voltage V_{REF} have fixed known values.

The range extension circuit has to ensure that the charge transfer within the sensing capacitance C_{SENS} remains within the input range of the AD7745/AD7746. To achieve this, the excitation voltage needs to be decreased by a factor of F, so that the sensing capacitance connected to the input can be increased by a factor F.

The AD7745/AD7746 have two independent excitation sources EXCA and EXCB. For the range extension, the excitation sources have to be set up in a way that EXCB is the inverse of EXCA. With resistor R1 and R2 connected as shown in Figure 1, the resulting range extension factor F is the ratio of the AD7746 excitation voltage between EXCA and EXCB ($V_{EXC(A-B)}$) and the attenuated excitation signal (V_{EXCS}) at the positive input of the AD8515 op amp. The range extension factor F can be calculated as follows:

$$F = \frac{V_{EXC(A-B)}}{V_{EXCS}} = \frac{R1 + R2}{R1 - R2}$$

By using both excitation sources, the mean voltage of the attenuated excitation voltage EXCS remains around $V_{DD}/2$.

The AD8515 operational amplifier in the circuit functions as a low impedance source to ensure the sensing capacitance C_{SENS} is fully charged when the AD7745/AD7746 starts sampling.

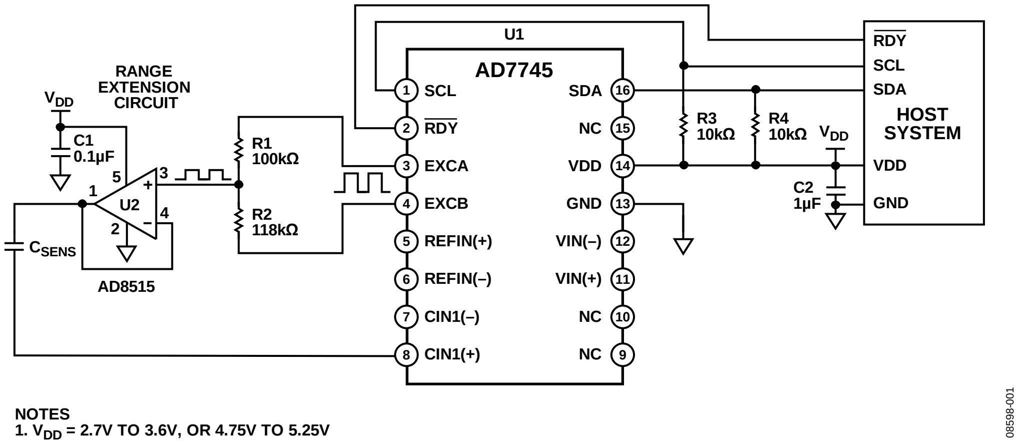

Figure 1. AD7745 Capacitive Input Range Extension Circuit (Simplified Schematic: Decoupling and All Connections Not Shown)

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Characteristics of Capacitive Humidity Sensor

The example of a common capacitive polymer humidity sensor element is used to explain the required calculation and considerations for the input range extension of the AD7745/AD7746. Typical technical data of such a capacitive sensor element are shown in Table 1.

Table 1. Typical Technical Data for Capacitive Sensor Element

Humidity Range	0% to 100% Relative Humidity (RH)
Capacitance	150 pF ± 50 pF (at 23°C and 30% RH)
Rate of Rise	0.25 pF/%RH

Calculating the Required Range Extension Factor, F

The first task is to find out which of the sensor's parameters is the main contributor for the required range extension.

The sensor's bulk capacitance can be as high as 200 pF, resulting in a required range extension factor of

$$F_{FIX} = \frac{200\text{ pF}}{17\text{ pF}} = 11.76$$

The sensor's dynamic range is calculated

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

The range extension factor required for the dynamic range is calculated as follows:

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

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

Choosing the Resistor Values R1 and R2

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 $F = 11.76$

$$R2 = \frac{100\text{ k}\Omega \times (11.76+1)}{(11.76-1)} = 118.587\text{ k}\Omega$$

$R2 = 118$ kΩ (from E96 resistor table)

The resistor values of 100 kΩ for R1 and 118 kΩ for R2 result in a range extension factor of

$$F = \frac{100\text{ k}\Omega + 118\text{ k}\Omega}{100\text{ k}\Omega - 118\text{ k}\Omega} = 12.111$$

Using the CapDAC

The AD7745/AD7746 have CapDACs that can be used to compensate for the bulk capacitance of a sensor element.
For the AD7745/AD7746, the CapDACs have a full-scale value of 17 pF minimum and 21 pF typical. Therefore, for a given CapDAC setting, the capacitances can vary significantly from part to part. The reason for this is that the AD7745/AD7746 on-chip capacitances can vary with the production process from batch to batch. However, the ratio variation between the on-chip capacitances is very small.

The AD7745/AD7746 capacitive input is factory calibrated. This calibration factor is stored in the Cap Gain Register. The calibration factor stored in the Cap Gain Register is calculated as follows:

$$F_{GAIN\_CAL} = \frac{(2^{16} + GAIN\_CAL)}{2^{16}}$$

Hence, the internal reference capacitance C_{REF} can be defined as the product of the AD7745/AD7746's allowed full range input capacitance and the gain calibration factor.

$$C_{REF} = 4.096\text{ pF} \times F_{GAIN\_CAL}$$

The AD7745/AD7746 are designed so that the ratio between full-range CapDAC capacitance and internal reference capacitance C_{REF} is 3.2. Therefore, the CapDAC full range can be calculated as follows:

$$C_{CAPDAC} = C_{REF} \times 3.2$$

If the gain calibration factor is 1.4, the resulting C_{REF} and C_{CAPDAC} values are as follows:

$$C_{REF} = 4.096\text{ pF} \times 1.4 = 5.7344\text{ pF}$$
$$C_{CAPDAC} = C_{REF} \times 3.2 = 18.3501\text{ pF}$$
$$C_{LSB\ CAPDAC} = \frac{18.3501\text{ pF}}{127} = 0.1445\text{ pF}$$

The range extension circuit ensures that the charge transfer within the sensing capacitance C_{SENS} remains within the input range of the AD7745/AD7746. Taking charge from the sensing capacitance at the CIN input, by the CapDAC, results in a decrease in measured capacitance. This is used to compensate for a sensor's bulk capacitance. One LSB of the CapDAC capacitance represents compensation on the sensing capacitance of

$$C_{DAC\ EFF} = C_{LSB\ CAPDAC} \times F$$
$$C_{DAC\ EFF} = 0.1445\text{ pF} \times 12.111 = 1.7499\text{ pF}$$

Calculating the Required CapDAC Setting

The CapDAC has some dynamic nonlinearity (DNL). It is recommended to setup the CapDAC to have the intended calibration point of the application at zero-scale of the capacitive input range. The remaining offset can then be easily calibrated by using the available system offset calibration function.

The required CapDAC setting for our humidity sensing element example is calculated as follows:

$$DAC_{SET} = \frac{C_{SENSOR}}{C_{DAC\ EFF}}$$

$$DAC_{SET} = \frac{150\text{ pF}}{1.7499\text{ pF}} = 85.72 \rightarrow 86\ (0x56)$$

A system offset calibration will compensate for the small remaining offset.

Measurement Using the Range Extension Circuit

An AD7746 demo board with a range extension circuit was used to perform the measurements. A variable capacitance was used during the measurement. The board was connected to a standard AD7746 evaluation board; the standard evaluation board software was used to configure the device and to read the conversion results. Circuits such as these must be constructed on a multilayer PC board with a large area ground plane. Proper layout, grounding, and decoupling techniques must be used to achieve optimum performance (see *Tutorial MT-031, Grounding Data Converters and Solving the Mystery of "AGND" and "DGND"* and *Tutorial MT-101, Decoupling Techniques*).

The variable capacitance was set to a defined value using a precision LCR meter. This capacitance was then connected to the range extension board, where the CapDAC was set to the calculated value of this defined bulk capacitance C_{BULK}. A system offset calibration was performed to have the zero point at C_{BULK}.

For each measurement taken, the capacitance was set to the desired value using the LCR meter, then connected to the range extension board measuring the capacitance seen by the AD7746. Finally, the extended capacitance value was calculated using the factor resulting from the measured resistor values. The following bulk capacitance values were used: C_{BULK} = 100 pF, 150 pF, and 200 pF.

Calculations for the Range Extension Circuit

From the previous calculations, we know the required resistor values are 100 kΩ and 118 kΩ. The resistors used were measured and had the following values: R1 = 100.004 kΩ; R2 = 118.060 kΩ.

The resulting range extension factor *F* is calculated

$$F = \frac{100.004\ \text{k}\Omega + 118.060\ \text{k}\Omega}{100.004\ \text{k}\Omega - 118.060\ \text{k}\Omega}$$

$$F = 12.07709$$

Calculating the dynamic capacitive input range,

$$C_{DYN} = 12.07709 \times (\pm 4.096\ \text{pF}) = \pm 49.4678\ \text{pF}$$

The resulting range for the measurement is ±45 pF in steps of 15 pF.

Calculating the gain calibration factor value read out: 0x5FBD = 24509

$$F_{GAIN\_CAL} = \frac{2^{16} + 24509}{2^{16}} = 1.373978$$

Resulting CapDAC values and settings are

$$C_{CAPDAC} = 4.096\ \text{pF} \times 1.373978 \times 3.2 = 18.009\ \text{pF}$$

$$C_{LSB\ CAPDAC} = \frac{18.009\ \text{pF}}{127} = 0.141803\ \text{pF}$$

$$C_{DAC\ EFF} = 0.1418\ \text{pF} \times 12.07709 = 1.71257\ \text{pF}$$

$$DAC_{SET100} = \frac{100\ \text{pF}}{1.71257\ \text{pF}} = 58.39 \rightarrow 58\ (0x3A)$$

$$DAC_{SET150} = \frac{150\ \text{pF}}{1.71257\ \text{pF}} = 87.59 \rightarrow 88\ (0x58)$$

$$DAC_{SET200} = \frac{200\ \text{pF}}{1.71257\ \text{pF}} = 116.78 \rightarrow 117\ (0x75)$$

Measurement Errors

From Figure 2, the measurement shows that the error caused by the range extension circuit is not dependent on the bulk capacitance value measured but on the range extension circuit itself. All three measurements show similar behavior and are linear; therefore, the error caused by the range extension circuit can be easily compensated for in software.

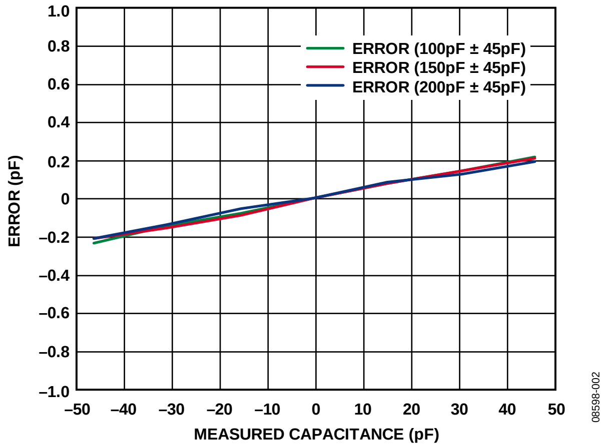

Figure 2. Gain Error vs. Measured Capacitance

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Webinar: *Leveraging Advanced Converter Architectures for Impedance and Capacitance Sensors.* Analog Devices.

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

AD7745/AD7746 Data Sheet

AD7745/AD7746 Evaluation Board

AD8515 Data Sheet

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CN08598-0-10/09(0)

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