Resonance-Based Capacitive Sensing Using LDC2114

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ABSTRACT

Capacitive sensing can be used to implement proximity detection or touch applications for various smart devices and equipment. In this application note, we review the advantages of Texas Instruments' resonance-based approach to capacitive sensing, followed by a discussion of the features and configurations of our third generation resonance-based sensing IC, the LDC2114. We also provide some guidelines in sensor design by characterizing the relationship between detection range and sensor size for the LDC2114, using a square copper plate as the sensor . The simplicity and flexibility of the sensor design allows it to be easily incorporated into a wide range of systems that require proximity or touch applications.

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1 Introduction

Texas Instruments' innovative resonance sensing uses a sensor based on a parallel LC resonator. Any change in the inductance or capacitance of the sensor will change the sensor frequency. To measure a capacitance variation, the LC resonator is constructed with a fixed inductor, and to measure an inductance variation, the LC resonator uses a fixed capacitor. From this principle, the resonant sensing device performs two basic functions - first, it injects energy synchronized to the natural oscillation frequency of the the sensor, and it accurately measures the sensor frequency. For applications requiring capacitance measurements, a conductive sensor plate is attached to one node of the LC tank to serve as the capacitive sensor. When a target, e.g. a human hand, approaches the sensor plate, it causes a change in capacitance of the system, which translates to a change in frequency that can be measured by the device.

The LDC2114's capacitive sensing capabilities provide the same advantages as discussed in *Capacitive Proximity Sensing Using FDC2x1y*. For example, the LC resonator also serves as a bandpass filter, which makes the system less prone to electromagnetic interferences (EMI) from noise sources. Another advantage is that this architecture can support much larger total sensor capacitances than other approaches.

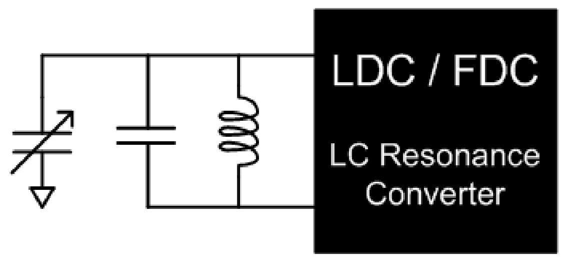

Figure 1. Schematic of LC Resonance-Based Capacitive Sensing using LDC or FDC

2 Features of LDC2114

The LDC2112/LDC2114 is a multi-channel low-noise inductance-to-digital converter with integrated algorithms that also support capacitive sensing applications. The multiple channels can be configured independently to measure either inductance or capacitance changes. It is an excellent choice for capacitive sensing in mobile applications where both high measurement resolution and low power consumption are important considerations. The block diagram of the LDC2114 is shown in Figure 2.

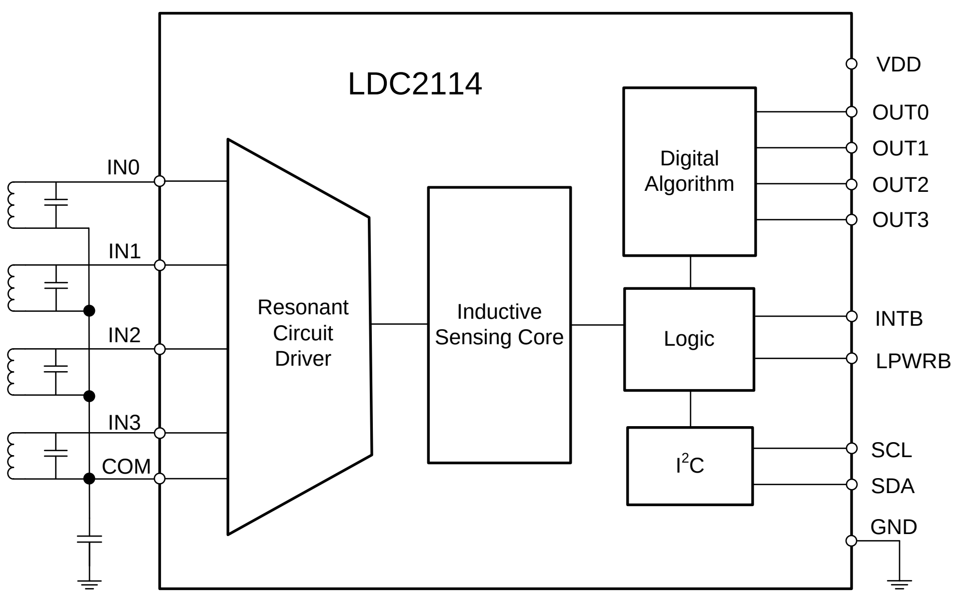

Figure 2. LDC2114 Block Diagram

The LDC2114 provides four channels of sensing; each channel can be independently enabled. The LDC2112 is a two channel variant of the LDC2114. Note that for the LDC2112, both channels are always enabled. The LDC2112/4 periodically measures all active channels at an adjustable interval, processes the sensor frequency shifts using internal algorithms to determine whether the measurements correspond to user interaction, enter a low power mode to save power, and then repeats the process.

When using LDC2114 for capacitive sensing, the capacitive sensor should be connected to the appropriate IN*n* (*n* = 0, 1, 2, or 3) pin. A change in AC capacitance results in a change in the oscillation frequency of the LC resonator (Refer to Section 3.3 for the exact formula).

Unlike TI's FDC devices, the LDC2114 can only be used to measure a dynamic change in capacitance; the integrated baseline tracking makes it unsuitable for measuring fixed capacitances. For many applications, such as HMI systems, this restriction does not matter.

2.1 Data Polarity, Reporting, and Microcontroller-less Operation

To use the LDC2112/LDC2114 as a capacitance sensing device, set the data polarity bit (DPOL*n*) for the corresponding channel to b0. Each channel can be set independently by configuring bits [0:3] in Register OPOL_DPOL.

Proximity detection or touch events may be reported by two methods. The first method is to monitor the OUT*n* pins (*n* = 0, 1, 2, or 3), which are push-pull outputs and can be used as interrupts to a microcontroller. The polarities of these pins are programmable. For more information on the triggering threshold, refer to the *LDC2114 Datasheet*. Any detection event or error condition is also reported by the interrupt pin, INTB, whose polarity is configurable through Register INTERPOL.

The OUT pins can be used to drive LED indicators and enable complete system operation without a microcontroller. This allows for compact system design with a small form factor and very low cost.

The second method is by use of the LDC2112/LDC2114's I^2C interface. The OUT register contains the fields OUT0, OUT1, OUT2, and OUT3, which indicate when a proximity or touch event has been detected. For more advanced functionality, the appropriate output DATA*n* registers can be retrieved for all active buttons, and processed on a microcontroller. The polarity is configurable in Register OPOL_DPOL. The I^2C data can be used to implement multi-function touch buttons, where the data value is correlated to the amount of force applied to the button or the magnitude of capacitive interaction by the user.

2.2 Temperature Compensation

The LDC2112/LDC2114 incorporates a baseline tracking algorithm to automatically compensate for slow changes in the sensor output caused by environmental variations, such as temperature drift and component aging. The device supports two modes of operation, a Normal Power Mode which samples the active channels more often for more responsive interactions, and a Low Power Mode which lowers the sample rate to reduce power consumption.

In Normal Power Mode, the effective baseline increment per scan cycle is 2^{NPBI} / 72, where NPBI is configured in Register NP_BASE_INC. In Low Power Mode, the effective baseline increment per scan cycle is 2^{LPBI} / 9, where LPBI is configured in Register LP_BASE_INC.

It is recommended to set a baseline tracking value high enough so that the output DATA*n* is centered around 0 with the range of environmental shifts the system will be exposed to. Setting the baseline tracking faster than necessary may reduce sensitivity.

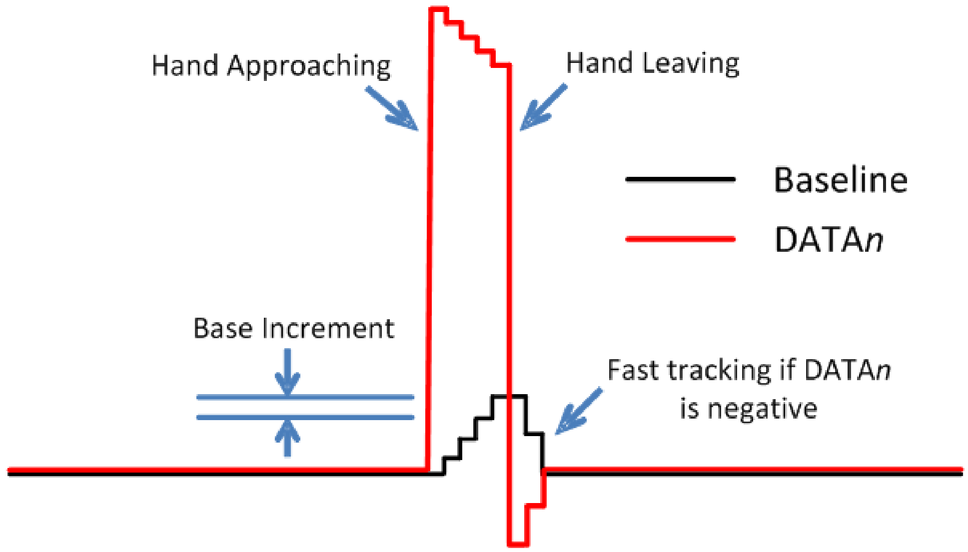

Figure 3. Baseline Tracking for LDC2114 when a Hand Approaches the Sensor

2.3 Sensitivity and Noise Floor

In designing a capacitive sensing system, it is useful to obtain two parameters. The first is the system noise floor at steady state. The actual noise floor can only be obtained with the fully assembled PCB and sensor. At the beginning of the design process, a prototype that mimics the final system can be sufficient to get an approximate value. The noise floor corresponds to roughly the minimum capacitance that can be easily distinguished in a system.

The second is the dynamic range of the signal, which is the maximum amount of capacitance change that can occur for a given application. For LDC2114, these parameters can be obtained by reading the DATA*n* registers under appropriate test conditions. The LDC2114EVM and the Sensing Solutions GUI are useful tools for this step.

Each LDC2114 channel has a dedicated sensitivity adjustment, which is controlled by the corresponding GAIN*n* register. The sensitivity can be varied across a range of 232 times with 64-levels. Each gain step increases the sensitivity by approximately 9%.

For systems using the LDC2114's built-in threshold level and sensing algorithms for detection, it is necessary to set the GAIN*n* to scale the signal to the appropriate level, so that the OUT*n* pin is triggered by a desirable signal. Alternatively, the signal response can read from the DATA*n* registers.

3 LDC2114 Electrical Parameters

The LDC2112/LDC2114 sensor is based on an LC resonator, which is composed of an inductor in parallel with a capacitor.

The primary electrical parameters for an LDC2114 sensor are:

- Inductance L
- Capacitance C
- Resonant Frequency f_{SENSOR}
- Resistance (represented as R_P or R_S)
- Quality Factor Q

3.1 Fixed Sensor Inductance

A fixed shielded inductor of 1 µH to 10 µH is needed for LC oscillation. The self-resonance frequency of the inductor should be at least twice the sensor frequency to avoid unstable behavior. Using a larger fixed inductor permits the use of a smaller sensor capacitor. Note that the parasitic capacitance of the inductor should be much smaller than the fixed capacitor.

The inductor should be shielded to prevent magnetic coupling with other circuits which could increase the measurement noise.

3.2 Fixed Sensor Capacitance

A fixed capacitor is needed for stable sensor oscillation. The highest measurement sensitivity is obtained with a sensor capacitor of about 10 pF. However, for some systems, noise and interference may require a larger capacitor (> 100 pF) for lower noise measurements. This may require some system evaluation to find the optimal value. It is recommended to use C0G/NP0 capacitors or other high quality dielectic capacitors to minimize noise and drift.

3.3 Sensor Frequency

The inductance and capacitance determine the sensor frequency based on Equation 1:

$$f_{SENSOR} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The capacitance here is the total parallel capacitance, which includes the fixed sensor capacitor, as well as parasitic capacitances of the PCB and device pins.

In general, as the sensor's conductive plate interacts with a target, the effective capacitance increases, causing the sensor frequency to decrease.

For optimal noise performance of the LDC2114, configure the sensor frequency to be in the range of 3 MHz to 25 MHz.

3.4 Sensor R_P and R_S

R_P represents the parallel resonant impedance of the oscillator, and R_S represents the series resonant impedance. These resistances are different representations of the same parasitic losses. It is important to remember that these resistances are AC resistances, and not the DC resistances. A lower R_P corresponds to a higher R_S, which increases power consumption.

The R_P can be calculated from the R_S by Equation 2:

$$R_P = \frac{L}{R_S \times C} \tag{2}$$

3.5 Sensor Quality Factor

The sensor Q, or quality factor, is the ratio of the sensor inductance to the sensor's AC resistance at a given frequency. In general, a higher value is desirable, as the sensor has a narrower band which is more resistant to noise, and also requires less energy to maintain oscillation for lower power consumption. The sensor Q can be calculated with Equation 3:

$$Q = \frac{1}{R_S}\sqrt{\frac{L}{C}} \tag{3}$$

The R_S is the sensor's series AC resistance at the frequency of operation. The sensor Q can be increased by increasing the sensor inductance, decreasing the sensor R_S, or decreasing capacitance.

When choosing an inductor, it is recommended to look for Q of at least 10 at desired sensor resonance frequency. It is best to measure Q at the expected oscillation frequency using an impedance analyzer or VNA.

3.6 Device Operating Region

The LDC2112/4 requires that attached sensors meet the following parameters:

- 1 MHz ≤ f_{SENSOR} ≤ 30 MHz
- 350 Ω ≤ R_P ≤ 10 kΩ
- 5 ≤ Q ≤ 30

If the sensor parameters are not within these specifications, the LDC2112/LDC2114 may not be able to measure frequency shifts, and as a result will not indicate capacitive detection events.

3.7 Device Settings

The measurement time interval for each LDC2112/4 channel is configurable to between 0.5 ms to 8 ms. A longer measurement interval will have lower noise, but will increase device current consumption. For most applications, setting the measurement time interval to 1 ms provides an optimum balance.

Each channel has an independent gain setting which adjusts the sensitivity of the sensor. The gain can be set from 1x to 232x in 64 steps. If the Gain setting is too low, the system may miss most or all user interactions. If the Gain setting is too high, noise may result in spurious detections. Generally, the Gain is configured during system prototyping by adjusting the value until the minimum interaction is detected with a SNR of 6, although some systems may permit a lower or higher SNR.

4 Detection Range Characterization

To characterize the relationship between sensitivity and sensor size, a proximity test was performed with the LDC2114 for various sensors with a human hand acting as the target. The hand starts from far away and gradually approaches the sensor. When the output signal changes by more than the peak-to-peak noise, it is considered a positive detection. The distance between the hand and sensor is recorded in Figure 4. As expected, the detection range increases as the sensor size increases.

The data below is collected using standalone square copper sensors attached to the LDC2114 EVM. If there is a ground plane close to the sensor, it will reduce the sensitivity and detection range. For more information on the effect of a nearby ground plane, refer to *Capacitive Proximity Sensing using FDC2x1y*.

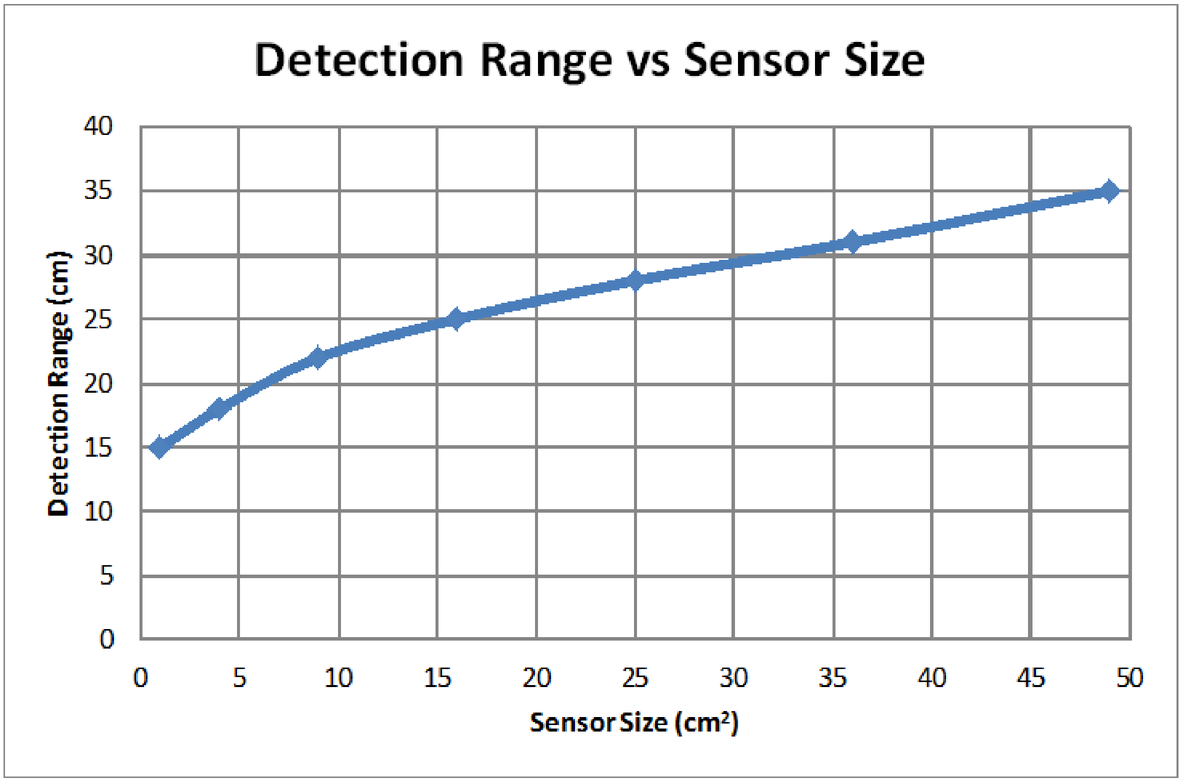

Figure 4. Detection Range vs Square Sensor Size Using LDC2114

5 Design Procedure

The design of a proximity sensing system using LDC2114 is straightforward. There are three major steps:

1. Choose the appropriate L and C
2. Pick the conductive sensor plate of a suitable size
3. Program the registers according to the sensor electrical parameters

Typically the inductor value is not very critical. A shielded surface inductor of about 5-10 µH is suitable for this purpose. The self-resonant frequency should be at least twice the sensor oscillation frequency. If prototyping with the LDC2114EVM, the inductor can be easily added to the EVM by soldering it between the IN*n*n pin and COM pin.

Selecting the fixed capacitor involves a tradeoff on noise and stability. A larger capacitor is better for stability, but a smaller capacitor provides better sensitivity. Typically, there is about 40 pF of additional parasitic capacitance which can shift with environmental changes. A small surface mount capacitor (less than 20 pF) is usually recommended for good sensitivity.

As an example, the desired sensor oscillation frequency for a system is around 8-10 MHz. This can be achieved by choosing an inductor of 5 µH, with self-resonant frequency of 40 MHz. If the total sensor plus parasitic capacitance is 40 pF, add a fixed surface mount capacitor of 10 pF to set the total capacitance to 50 pF.

With a 5 µH inductor and a 50 pF capacitance, the sensor oscillation frequency is roughly 10 MHz. If the total AC resistance including all parasitics is 12 Ω, the Q would be 26 and the R_P would be 8 kΩ. This sensor is well within the LDC2114 operating region as indicated in Figure 2. If the sensor R_P is outside of the operating region of the LDC2112/4, consider using a higher Q inductor or reducing the sensor capacitance.

The next step is to choose the appropriate sensor plate size. Refer to Figure 4 as a reference. Please note that the data is for a standalone sensor plate far away from ground planes. On a real system board with ground plane and other interferences, the detection distance can decrease significantly depending on how close those interferences are. It is recommended to move any ground plane as far away from the sensor as possible.

After choosing the sensor components, the last step is to program the LDC2114 registers according to the sensor electrical parameters. The sensor frequency, R_P, and Q values must be within the the device operating region. It is recommended to measure the actual sensor parameters instead of just relying on theoretical calculations in order to take all the parasitics into consideration.

If Ch0 is being used, and the desired sampling window is 1 ms per cycle at the default 40 scan cycles per second, the following register fields must be set based on the sensor electrical parameters.

Table 1. Example Register Settings

Register	Bits	Field	Value
0x0E	5:0	GAIN0	b11 1100
0x17	2:0	LCDIV	b010
0x1C	0	DPOL0	0
0x1E	1:0	CNTSC0	b00
0x20	7	RP0	1
0x20	6:5	FREQ0	b01
0x20	4:0	SENCYC0	b1 0011

For more information on the LDC2114 register configurations, refer to the *LDC2114 Datasheet*.

6 Summary

In this application note, the features of Texas Instruments' resonance-based LDC2114 are reviewed, along with its suitability for capacitive sensing. The LDC2114 provides easy configuration to enable proximity and touch applications, and supports a wide range of sensor construction. It achieves an excellent detection range using a simple copper sensor.

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