

Configuring Inductive-to-Digital-Converters for Parallel Resistance (R_p) Variation in L-C Tank Sensors

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Sensor Signal Path

ABSTRACT

This application note reviews sensor R_p configuration for LDC devices. The devices covered in this note include:

- LDC100x
- LDC1041
- LDC1051
- LDC1312
- LDC1314
- LDC1612
- LDC1614

Clear understanding on how to set the R_{p_MIN} and R_{p_MAX} registers is necessary for not only R_p measurements, but also for optimum L measurements.

The fundamental principle of R_p measurements is that magnetic fields from an LC circuit generate eddy currents on the surface of nearby conductive materials. These currents appear as additional parasitic resistance in the LC circuit. The energy dissipated as heat due to this resistance is lost, and LDC devices can measure this loss. The amount of parasitic resistance generated by eddy currents is a function of the inductor shape, distance between inductor and conductive target, temperature, and the target composition.

R_p configuration is quite different for LDC10xx devices and LDC13xx/16xx devices.

- While the LDC131x and LDC161x devices do not measure R_p , they still need to be configured to accommodate the change in R_p as the target moves. Due to the different architecture between the LDC10xx family of devices and the LDC131x and LDC161x devices, the process is different.
- LDC10xx devices use R_{p_MIN} and R_{p_MAX} settings to determine minimum and maximum amount of energy inserted into the resonator. The converters are also able to measure the amount of energy dissipated at each point of time. Therefore, resistive losses can be determined, and proximity values are used as the output.

LDC13xx/16xx devices use only one register setting, represented as drive current, to configure the maximum amount of energy inserted into the resonator. The current drive is usually constant during normal operation.

Contents

1	What is R_p and How it is Derived?	2
2	Determining System R_p	4
3	Meeting R_p Boundary Conditions of LDC100x, LDC1041, and LDC1051	4
4	Setting R_{p_MAX} and R_{p_MIN} for Proper Operation of LDC10xx Devices	6
4.1	Setting R_{p_MAX} and R_{p_MIN}	6
4.2	Limiting Cases.....	6
5	Meeting R_p Boundary Conditions of LDC1312, LDC1314, LDC1612, and LDC1614.....	7
6	Setting the Current Drive LDC1312, LDC1314, LDC1612, and LDC1614	7
7	Conclusion	9

List of Figures

1	Series Electrical Model of an LC Tank.....	2
2	Parallel Electrical Model of an LC Tank	3
3	R_p [k Ω] Versus Distance [mm] of a 14-mm Diameter PCB Coil	4
4	LDC10xx Change of the Oscillation Amplitude set by R_{p_MIN} , R_{p_MAX}	5
5	LDC13xx/LDC16xx Sensor Amplitude set by DRIVE_CURRENT_CHx.....	7

List of Tables

1	Current Drive as a Function of Parallel Resistance	8
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1 What is R_p and How it is Derived?

TI's Inductance to Digital Converters (LDCs) use an LC resonator to generate a magnetic field that is used to sense nearby conductive objects. For many applications, the location of a specific conductive object, generally referred to as the target, is desired. The sensor inductor can be a PCB coil, an unshielded wire-wound SMD inductor, or a spring. Texas Instruments' [LDC Sensor Design](#) application note provides details on coil design and sensor parameters.

An electrical model of an LC resonator is shown in [Figure 1](#). Ideally, an LC tank does not have a resistive component, and can oscillate forever with sustained excitation. For all real inductors, there is parasitic series resistance based on the conductor profile, sensor operating frequency, and the sensor geometry. The sensor can therefore be modeled as shown in [Figure 1](#), where the inductor and its parasitic resistance vary as a function of target proximity.

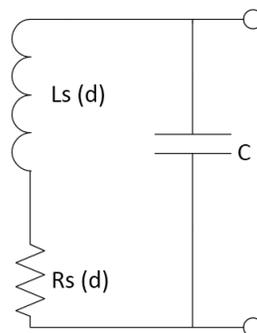


Figure 1. Series Electrical Model of an LC Tank

Figure 2 shows the Norton equivalent of the series electrical model at resonant frequency. In this model, $R_p(d)$ stands for the equivalent parallel resistance of the sensor, or resonant impedance. $R_p(d)$ is a function of the target position. The resonator can therefore be modeled as a distance dependent inductor, a fixed capacitor, and a distance dependent resistor in parallel.

Note that in either model, R_s and R_p are the AC resistances of the sensor, not the DC resistances. The AC resistance of an inductor increases with oscillation frequency because of skin effect, which is the tendency for AC signals to propagate on the surface of conductors.

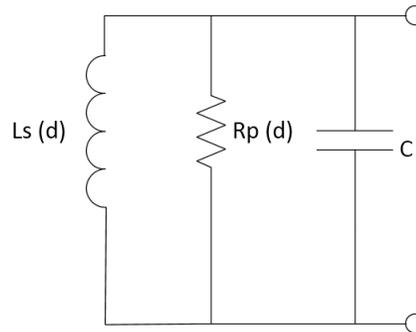


Figure 2. Parallel Electrical Model of an LC Tank

In the parallel model, the value of R_p can be calculated with:

$$R_p = \frac{L}{C \times R_s} \tag{1}$$

Parallel resistance as a function of series resistance, inductance, and capacitance is shown in Equation 1.

The variation of $L(d)$ and $R_p(d)$ as a function of distance (d) or conductor composition occurs due to the interaction of the magnetic field of the sensor with the conductive target object. The magnetic field generates eddy currents on the surface of the target, which in turn generate their own magnetic field. The magnetic field generated by eddy currents opposes the original field generated by the sensor. As the sensor and the target move closer together, the eddy currents in the target increase in intensity, and the opposing magnetic field strength increases. The result is that the R_p of the resonator and the observed inductance of the sensor decrease as the target moves closer to the sensor. This decrease in sensor inductance is apparent as an increase in the resonant frequency.

$$f_{\text{sensor}}(d) = \frac{1}{2 \times \pi \sqrt{L(d) \times C}} \tag{2}$$

Sensor frequency as a function of inductance and capacitance is shown in Equation 2.

With the LDC10xx family of devices, when R_p decreases, the LDC injects more energy into the resonator to maintain the oscillation. The additional energy dissipation is detected by the LDC and is reflected as a change of the output code. The change in R_p is a function of the shape, size, and composition of the conductive target. By measuring both the R_p change and the change in inductance, it is possible to determine metal composition.

Figure 3 shows the variation in R_p as a function of target distance for a 14-mm diameter PCB coil (23 turns, 4-mil trace width, 4-mil spacing between trace, 1-oz Cu thickness, FR4). The target is composed of 2-mm thick Stainless steel.

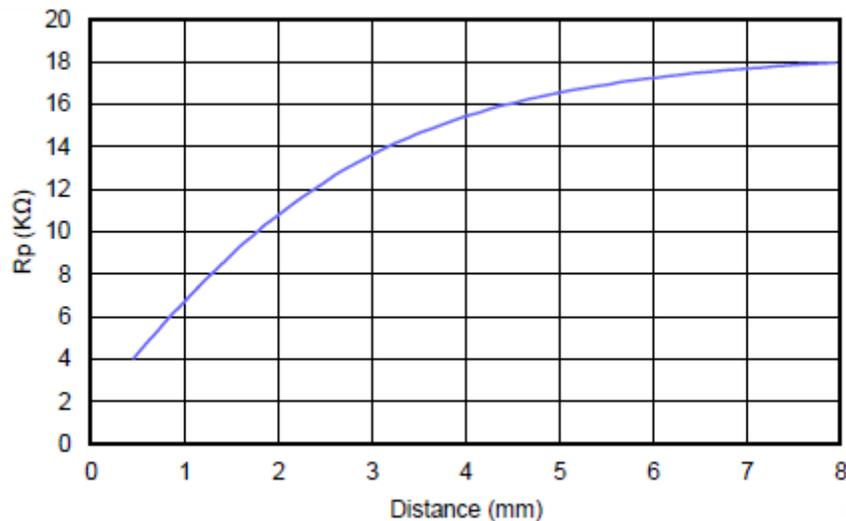


Figure 3. R_p [k Ω] Versus Distance [mm] of a 14-mm Diameter PCB Coil

2 Determining System R_p

1. For an air coil purchased from a third party manufacturer — obtain the following specifications at operating frequency: Q , L_s , and R_s from the data sheet of the coil. Then use [Equation 1](#), along with the capacitance value, to calculate R_p . This value represents the highest expected R_p value with no target.
2. For a PCB coil designed using WEBENCH, the parameters are provided by WEBENCH. Again, the R_p value reported in WEBENCH represents the maximum expected R_p .
3. For a PCB coil designed outside of WEBENCH, an impedance analyzer can be used to measure Q , L_s , and R_s of the sensor.

3 Meeting R_p Boundary Conditions of LDC100x, LDC1041, and LDC1051

LDC10xx devices are able to determine the amount of energy lost to eddy currents by regulating the oscillation amplitude. The LDC10xx devices have two programmable current drive values: R_{p_MIN} and R_{p_MAX} . Appropriate values must be set into registers 0x01 (R_{p_MIN}) and 0x02 (R_{p_MAX}).

When the LDC10xx drives R_{p_MIN} into the oscillator, it injects a higher current, and the energy in the oscillator increases. This additional energy is apparent as higher sensor amplitude. When the sensor amplitude exceeds the programmed threshold of 0x02 register, the LDC then drives a lower current into the sensor, and so the amplitude of the oscillator decreases.

[Figure 4](#) shows the sensor oscillation across the LDC10xx sensor pins, INA and INB. The current drive mode is overlaid onto the trace; notice the increasing amplitude as R_{p_MIN} is driven into the sensor.

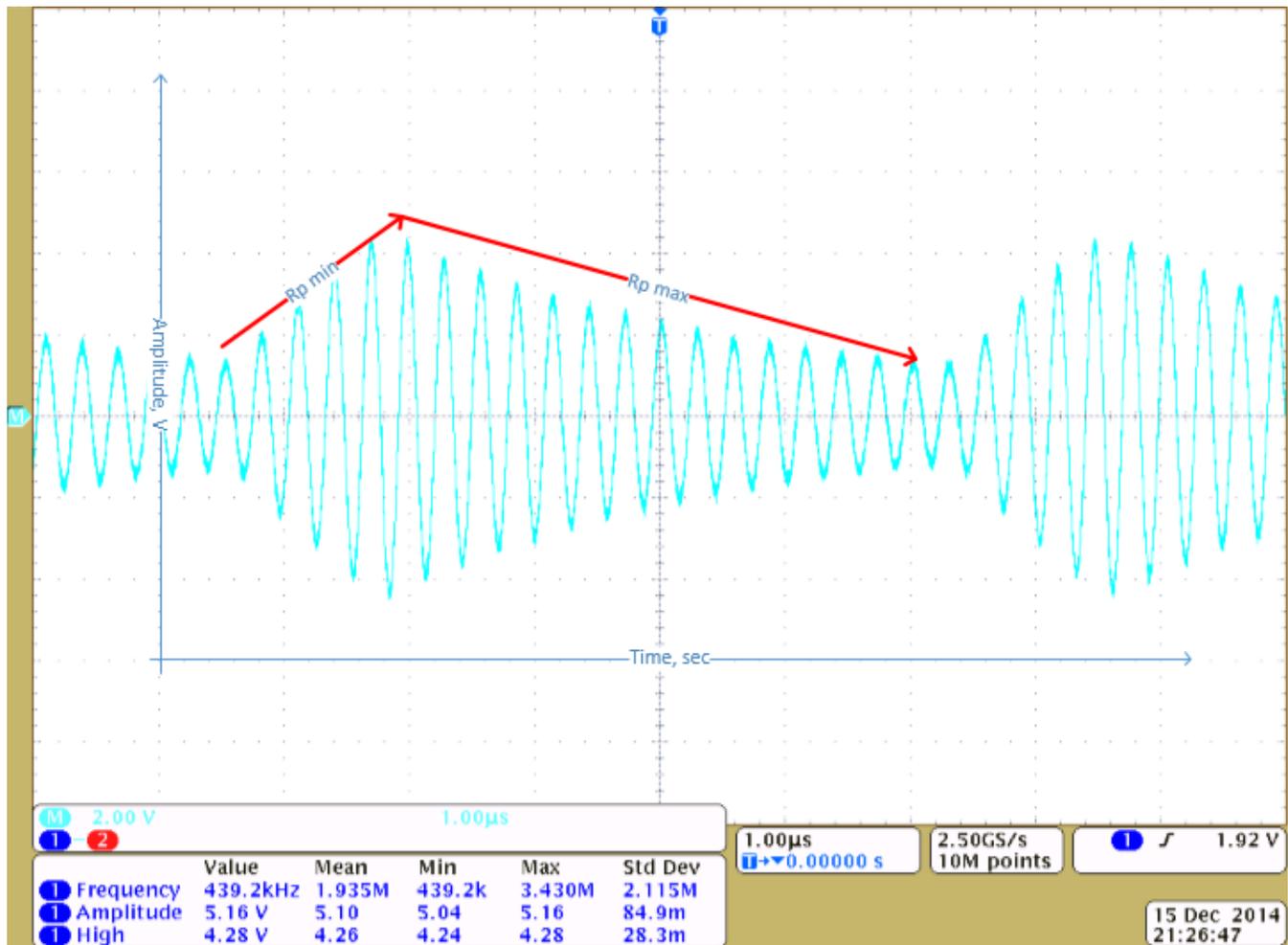


Figure 4. LDC10xx Change of the Oscillation Amplitude set by R_p_MIN , R_p_MAX

The principle of R_p conversion used by LDC10xx devices can be described as follows:

1. Voltage amplitude may be set to a constant level of 1 Vpp, 2 Vpp, or 4 Vpp. In general, the 4 Vpp is recommended for the majority of applications, as improved ENOB can be realized. Lower amplitude settings can be used to reduce the LDC10xx current consumption.
2. Device registers that are used to configure R_p_MIN and R_p_MAX settings are set to minimum and maximum amount of energy that LDC input into the resonator.
3. The LDC10xx alternates current drive as a function of target position. The LDC converts R_p change that falls within the limits to a digital value, shown as Proximity Data in the EVM GUI. Note that the R_p change must lie within the R_p_MIN and R_p_MAX limits.

The amount of power is determined by $P = VI$ or $P = V^2/R$. Due to the inverse relationship, R_p_MIN sets the maximum amount of power, while R_p_MAX determines the minimum amount. One might also think of $I_{MAX} = V/R_{MIN}$ and vice versa. Since the amount of current injected is a function of distance and conductor composition, this parameter can be used to measure distance and metal composition.

4 Setting R_p_MAX and R_p_MIN for Proper Operation of LDC10xx Devices

Various sensing applications may have different ranges of the resonance impedance R_p due to system design and implementation. The LDC10xx measurement range of R_p is controlled by setting two registers – R_p_MIN and R_p_MAX . For a given application, R_p must never be outside the range set by these register values, otherwise the measured value is clipped. For optimal sensor resolution, the range of R_p_MIN to R_p_MAX must be set to the minimum range that cover the maximum expected range of R_p . Properly setting the R_p range is necessary for effective proximity measurement and highest conversion resolution.

First, the R_p_MIN and R_p_MAX settings must meet sensor boundary conditions (that is, the range of R_p variation that the sensor experiences due to target movement). A detailed procedure on how to determine R_p_MIN and R_p_MAX is described in the next section; refer to the appropriate LDC10xx data sheet for additional information.

4.1 Setting R_p_MAX and R_p_MIN

Use the following procedure:

1. Set R_p_MIN to 0x3F, R_p_MAX to 0x00.
2. Expose the coil to the maximum metal coverage for the application (closest target position, thickest part, and so forth).
3. Start reducing R_p_MIN setting one code at a time, and take R_p Measurements (they go up with each change). To speed up tuning, it is also possible to change the value by more than one code at a time, for example by using binary search.
4. When R_p gets in the range of 20,000–30,000 codes, it is the optimal R_p_MIN setting.
5. Move the target to a position where it is exposed the least (farthest position, thinnest part, and so forth).
6. Start increasing R_p_MAX setting one code at a time, and take R_p Measurements (they go down with each change).
7. When R_p gets in the range of 2,000–3,000 codes, or the difference between R_p_MIN and R_p_MAX values reaches 25x to 26x, that is the optimal R_p_MAX setting. If too much noise, then back off one to two R_p_MAX codes.

4.2 Limiting Cases

There are two limiting cases for sensor range: low R_p and saturated R_p .

1. For the case of low value of R_p , system accuracy is affected. The data sheet of the LDC10xx indicates that the minimum acceptable R_p is 798 Ω . In the case when R_p is of a lower value, a series inductor must be added to the sensor network. The quality factor of the coil is a function of L , C , and R_s . If R_p is low, the quality factor is also low. System accuracy is affected by it because low Q coils are less immune to noise interference.

$$Q = R_p \times \sqrt{\frac{C}{L}} = \frac{1}{R_s} \times \sqrt{\frac{L}{C}} \quad (3)$$

Quality factor as a function of series resistance, inductance, and capacitance as shown in [Equation 3](#).

2. When the sensor R_p exceeds the programmed R_p_MAX value, the sensor amplitude exceeds the maximum acceptable range and the output saturates. The LDC10xx enters an invalid operating state. To avoid this scenario, the first option is to adjust R_p_MAX to a larger value. If R_p_MAX cannot be increased further, the sensor may need to be redesigned with a lower R_p . This can be done by either lowering L or increasing C .

5 Meeting R_p Boundary Conditions of LDC1312, LDC1314, LDC1612, and LDC1614

Although the LDC131x/161x family of devices does not measure R_p , the optimal configuration of these devices still requires attention to the effect of R_p on sensor performance. The current drive that these devices provide can accommodate R_p values in the range from 1 k Ω to 100 k Ω . The LDC131x/LDC161x devices do not vary the current drive, but instead are programmed to use a constant current drive. The current drive for each channel can be programmed to fall within a certain range of values. The channels are individually configured using their respective DRIVE_CURRENT_CHx register. Because the current drive is constant, it must be set so that as the R_p of the sensor varies over the operating range, the sensor oscillation amplitude remains with a useable range. The maximum allowable sensor amplitude is 1.8 V, while the minimum is determined by the requirements of the application. Note that as the sensor amplitude decreases to a few hundred millivolts in amplitude, the output SNR degrades. It is possible that as the target-to-sensor distance approaches zero, the oscillations completely stop. Figure 5 shows the sensor oscillation across the LDC13xx/16xx sensor INA pin. For any specific target position the sensor amplitude is constant.

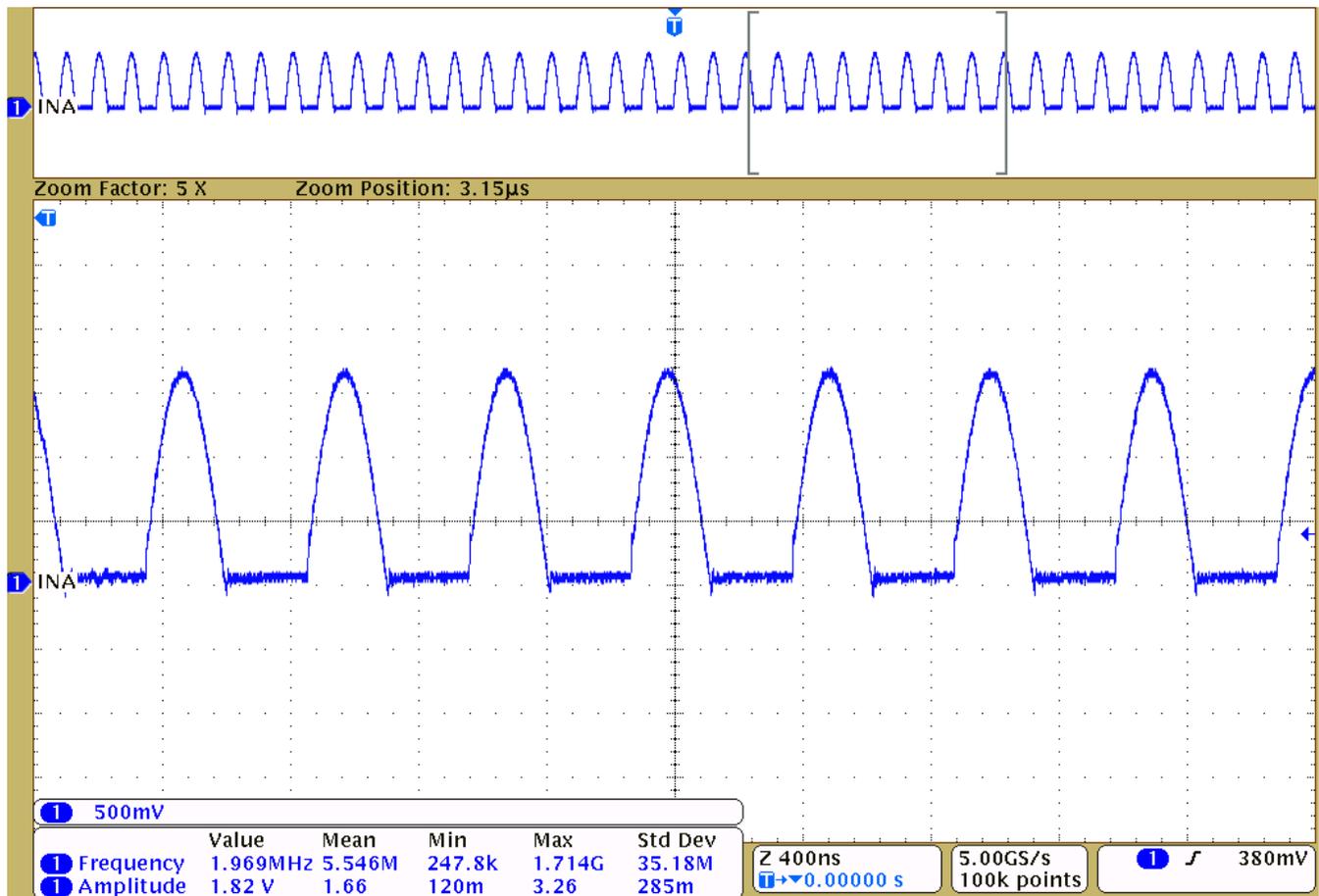


Figure 5. LDC13xx/LDC16xx Sensor Amplitude set by DRIVE_CURRENT_CHx

6 Setting the Current Drive LDC1312, LDC1314, LDC1612, and LDC1614

Current drive for LDC13xx/LDC16xx family of devices must be set according to the sensor R_p . If the value of R_p is known, the corresponding current drive can be found in Table 1. If the known R_p falls between two table values, approximate the sensor R_p to the lower value. The values in the 2nd column represent the current drive value that give oscillation amplitude of approximately 1.65 V for the given R_p . The hexadecimal equivalent must be written to the DRIVE_CURRENT_CHx register, in the CHx_IDRIVE field.

Table 1. Current Drive as a Function of Parallel Resistance

R_p, kΩ	Corresponding Current Drive, decimal
89.99	0
77.59	1
66.87	2
57.63	3
49.67	4
42.83	5
36.91	6
31.81	7
27.42	8
23.64	9
20.37	10
17.56	11
15.14	12
13.05	13
11.25	14
9.69	15
8.36	16
7.2	17
6.21	18
5.35	19
4.61	20
3.98	21
3.43	22
2.95	23
2.55	24
2.19	25
1.89	26
1.63	27
1.4	28
1.21	29
1.05	30
0.9	31

If the R_p is not known, the following steps for auto-calibration can be used to configure the needed drive current, either during system prototyping, or during normal startup, if feasible:

1. Set target at the maximum planned operating distance from the sensor
2. Place the device into SLEEP mode by setting CONFIG.SLEEP_MODE_EN to b1.
3. Program the desired values of SETTLECOUNT and RCOUNT values for the channel.
4. Enable auto-calibration by setting RP_OVERRIDE_EN to b0.
5. Take the device out of SLEEP mode by setting CONFIG.SLEEP_MODE_EN to b0.
6. Allow the device to perform at least one measurement, with the target stable (fixed) at the maximum operating range.
7. Read the channel current drive value from the appropriate DRIVE_CURRENT_CHx register (addresses 0x1e, 0x1f, 0x20, or 0x21), in the CHx_INIT_DRIVE field (bits 10:6). Save this value.
8. During startup for normal operating mode, write the value saved from the CHx_INIT_DRIVE bit field into the CHx_IDRIVE bit field (bits 15:11).
9. During normal operating mode, the RP_OVERRIDE_EN must set to b1 to force the fixed current drive.

If the current drive results in the oscillation amplitude greater than 1.8 V, the internal ESD clamping circuit becomes active. This may cause the sensor frequency to shift so that the output values no longer represent a valid system state. If the current drive is set at a lower value, the SNR performance of the system decreases, and at near zero target range, oscillations may completely stop, and the output sample values are all zeros.

7 Conclusion

TI's LDC devices require configuration based on the equivalent parallel resistance of the sensor, R_p .

For LDC100x, LDC1041, and LDC1051 devices the change of energy can be detected and transformed into proximity values. This can be used for various sensing applications, for example distance detection. R_p data is necessary for applications sensing the composition of the metal targets.

The inductance-only LDC1312, LDC1314, LDC1612, and LDC1614 use the maximum R_p value to set the sensor drive current, which determines amplitude level. R_p values set the current limits and therefore the energy the IC inserts into the resonator.

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (April 2015) to B Revision	Page
• Changed LDC1000 to LDC100x throughout	1
• Updated sentence structure for clarity throughout	1

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