

# LDC1000 Temperature Compensation

Evgeny Fomin

## ABSTRACT

LDC1000 is a high-precision Inductance-to-Digital converter with internal precision of 0.1% over dynamic range. However, other factors may influence measurement precision greatly, dominating the system performance. One of these is temperature variation.

This App Note will discuss the physical effects of temperature variation on inductive sensing and provide methods to mitigate these effects.

## Contents

1	Introduction .....	1
2	Temperature Variation Effects on System Parameters .....	1
2.1	$R_p$ Variation .....	1
2.2	Inductance Variation .....	2
3	Mitigation .....	4
3.1	$R_p$ Measurement with Temperature Correction .....	4
3.2	Multi-Coil Design .....	5
4	References .....	6

## 1 Introduction

The LDC1000 precisely measures the characteristics of a sensor (LC oscillator) to detect the presence of a conductive target. The characteristics of the coil need to be suited to the specific application, and any changes in the coil will affect the measurement sensitivity and accuracy. Shifts in the operating temperature of the system may need to be considered for the impact on some applications.

## 2 Temperature Variation Effects on System Parameters

Inductive sensing is based on measuring the variation of inductance,  $L$ , and resonance impedance,  $R_p$  of the sensor coil. Both of these parameters can be sensitive to temperature on coil design, material, and operating conditions. Temperature-induced effects in  $R_p$  are mainly due to temperature coefficients of the coil and target materials. Temperature-induced effects in  $L$  are a result of the temperature coefficient expansion of the coil structure. These effects are generally much smaller in magnitude. Therefore, measurements based on  $L$  are less sensitive to temperature variations.

### 2.1 $R_p$ Variation

The parallel resistance of the LC circuit,  $R_p$ , is one of the parameters measured by the LDC1000.  $R_p$  is based on the following formula:

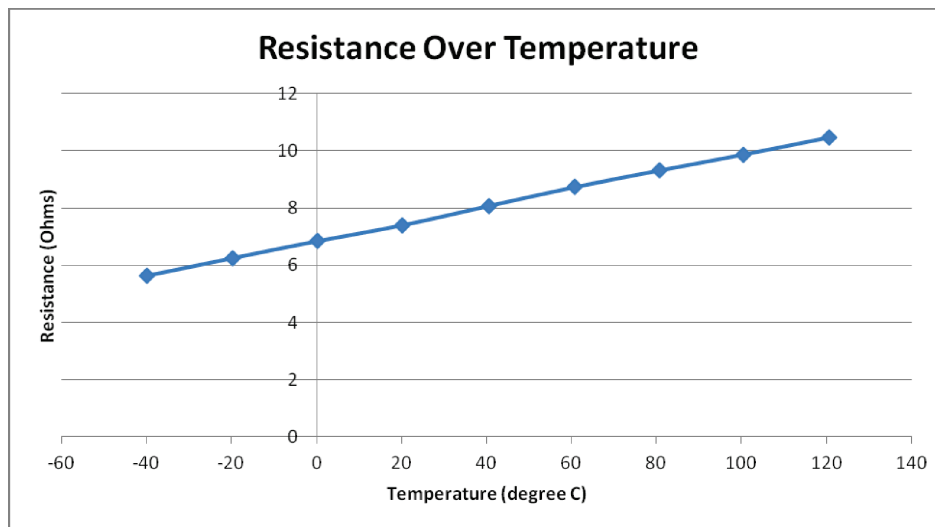
$$R_p = L / (R_s * C)$$

where

- $L$  is inductance
- $R_s$  is equivalent series resistance of LC tank
- $C$  is the capacitance of the LC tank.

(1)

The dominant factor is the change of resistivity of the coil and target. Copper has a resistive temperature coefficient of 0.39%/°C (3900ppm/°C). Many other metals have a similar value.



**Figure 1. Resistance of a Typical PCB Coil as a Function of Temperature**

The value of  $R_p$  also changes in conjunction with inductance, as described below. This is due to the proportionality of  $R_p$  to  $L$ .

## 2.2 Inductance Variation

In the absence of magnetic materials, such as ferrous metals and ferrites, the inductance depends only on current flow geometries. Those currents include the current in the coil itself, as well as all eddy currents induced in surrounding conductors. We will consider how temperature variation affects inductance of air-core coils.

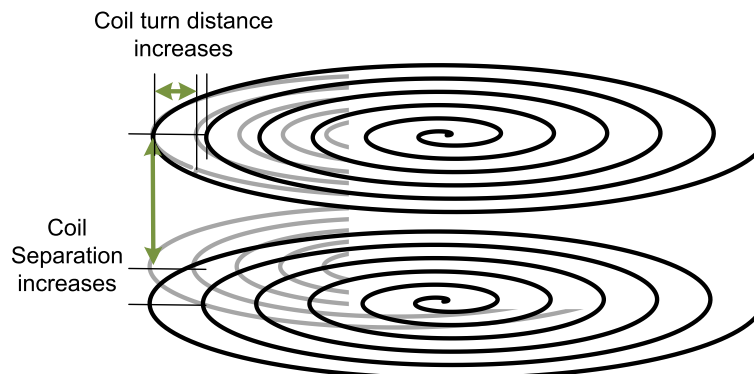
The coil geometry will change with the temperature variation due to thermal expansion or contraction of the coil. For wound copper coils, the coefficient of thermal expansion (CTE):

$$\alpha = 17 \times 10^{-6} / ^\circ\text{C} \quad [1] \quad (17 \text{ ppm}/^\circ\text{C}), \quad (2)$$

$L$  is typically proportional to the area of the coil divided by its length. Thus, the overall variation in  $L$  is also  $17 \text{ ppm}/^\circ\text{C}$ .

For PCB coils there are two cases to consider: a single-layer and multi-layer coil designs.

The inductance of a single-layer coil is proportional to its diameter [2], so a change in  $L$  is proportional to CTE of the substrate. The majority of PCBs use FR4 for the substrate, which has a CTE of  $\sim 15 \text{ ppm}/^\circ\text{C}$ .



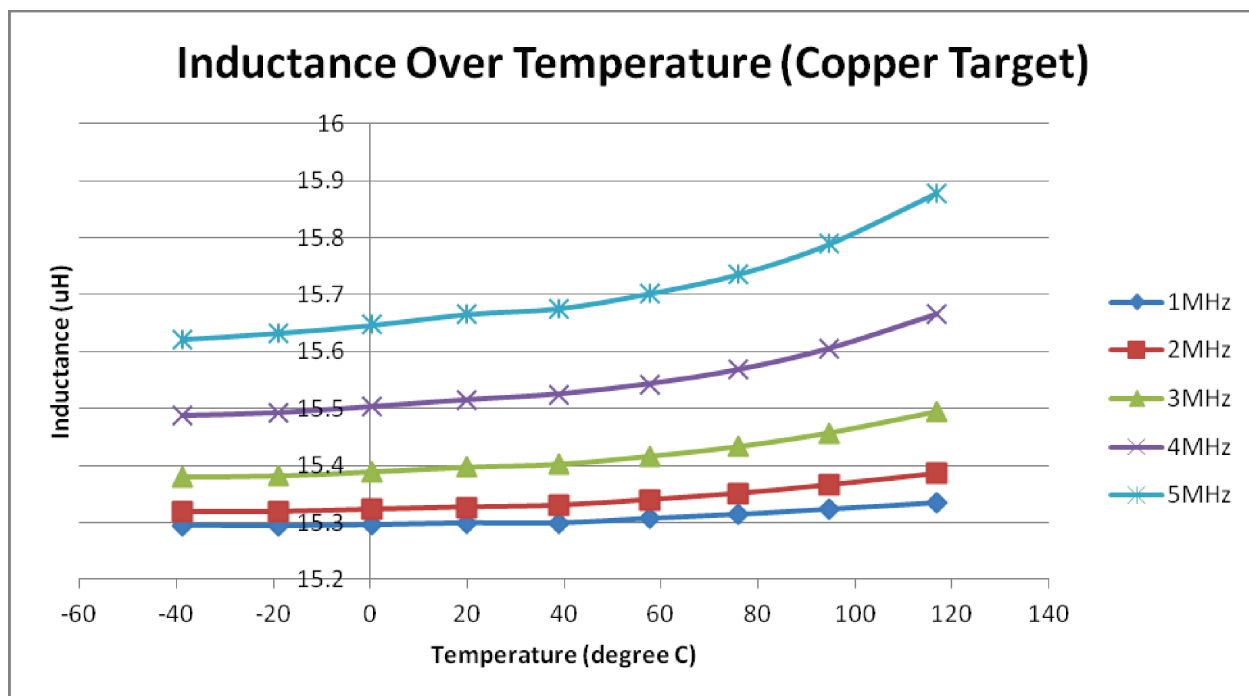
**Figure 2. Multi-Layer Coil Geometry Shift Due to Temperature**

Multi-layer coils have a more complex relationship between temperature and inductance variation due to changing of the coupling coefficients between different layers. Since the change in the PCB width will lead to a change of the coupling between layers, the effective inductance change will actually be smaller than 15ppm/°C. Moreover, with a special coil design, the increase in inductance due to diameter increase can be compensated by decrease in inductance due to thickness increase. In Figure 2, above, the shift in separation of the coils in a multi-layer coil design is compensated by the change in distance between turns of the coil.

Another effect to consider is the change in inductance due to change of the current distribution in the windings (proximity effect). Temperature change will change wire resistivity, which in turn will cause a change of the conductive skin depth. This effect, however, is much smaller than expansion-contraction of the PCB, and is more of an academic interest.

When a target is in proximity of the coil (<50% of the coil diameter distance), temperature effects on the mutual inductance need to be evaluated.

A temperature variation will change resistivity, and consequently eddy current distribution in the target. This change in eddy current distribution will impact mutual inductance. The magnitude of the impact depends greatly on the distance to target as well as frequency, and is on the order of tens of ppm when the target is very close to the coil, quickly dropping to single-digit ppm when the target is at a distance greater than 20% of the coil diameter.



**Figure 3. Inductance of a Coil as a Function of Temperature Across Frequency**

Another (and often more important) consideration is the mechanical configuration. Temperature changes may change the target-coil distance due to expansion-contraction of the mechanical system. Such a change has direct influence on the mutual inductance, especially when the target is very close to the coil. The exact effect depends on many factors, such as the coil and target separation, geometry, target composition, and so forth.

For example, on one of the systems under consideration, we found that relative change in L ( $\Delta L/L$ ) was equal to relative change in coil-target separation ( $\Delta X/X$ ) divided by 4. As the relative change in X may be large when X is small, care should be taken when designing mechanical system.

The LDC1000 measures inductance indirectly by measuring the oscillation frequency of the sensor (LC tank), and inductance is computed using the known capacitance of the LC tank:

$$F = 1 / (2\pi\sqrt{LC}) \quad (3)$$

Thus,

$$L = 1/(2\pi F)^2/C. \quad (4)$$

It is important to note that the value of the capacitance is also subject to temperature variations. To minimize this effect, C0G capacitors, which have a 30ppm/°C temperature coefficient, are recommended. For the inductors with magnetic cores the change in inductance over temperature will be dominated in most cases by change of permeability of the core. Exact calculation of such change depends on the core material and the shape of the coil, and is beyond the scope of this app note.

Whenever practical, such as when system performance requirements are met across temperature range, we advise using inductance-based measurements. The error due to temperature variation of less than 0.1% is achievable without any temperature compensation.

### 3 Mitigation

#### 3.1 $R_p$ Measurement with Temperature Correction

$R_p$  measurements can be easily corrected if temperature of the system during operation is known, and the coil and target are made of the same material (or materials with similar temperature coefficients of resistivity). We also assume that the coil and target temperatures are the same.

Initial system calibration (that is, LDC1000 output vs. distance/position/angle) should be recorded at controlled known temperature (25°C, for example). The LDC1000 measures  $1/R_p$  and reports it as a digital value. The real  $R_p$  value can be calculated according to the formula given in the datasheet.

Re-calculate calibration data to reflect  $R_p$  as a function of the parameter(s).

During system operation, data from the LDC1000 is converted to the real  $R_{pmeas}$  in Ohms according to the same formula, and then corrected for the temperature as following:

$$R_p = R_{pmeas} / (1 + \alpha(T - T_{cal}))$$

where

- $R_p$  is the corrected  $R_p$  value
- $R_{pmeas}$  is the measured  $R_p$  value
- $\alpha$  is the temperature coefficient of resistivity
- $T_{cal}$  is the temperature of system calibration
- $T$  is the operation temperature

(5)

The corrected  $R_p$  value is used to determine the parameter value from calibration data.

Using this compensation method, the temperature variation error can be reduced to less than 0.1%.

Tip: a second LDC1000 sensor can be used as a high-precision temperature sensor. The sensor has to be exposed to the same environment as the main sensor, but its output should not be influenced by the varying parameter (distance/position/angle of the target). Then the output of the second system can be calibrated as a function of the temperature, and can be used to measure temperature during system operation.

If temperature coefficients of a coil and a target are significantly different, or a coil with a magnetic core has to be used, or there are some other sources of non-linearity in temperature dependence present,  $R_p$  will no longer be linear with temperature. To correct for temperature variation in such case, a Look-up Table approach can be used.

The system performance is characterized across temperature range during the design (1-time calibration) where  $R_p$  vs. parameter (distance, position, angle, and so forth) is recorded at various temperatures.

During system operation, the appropriate curve of  $R_p$  vs. parameter is chosen according to current temperature and used to measure the parameter as a function of  $R_p$ .

Measurement precision can be further improved by using interpolation of calibration data to temperature values that are not present in cal data.

### 3.2 Multi-Coil Design

Another easy approach to compensate for the temperature variation is to add an additional sensor to the system design. The coil and target have to be of the same material and at the same temperature.

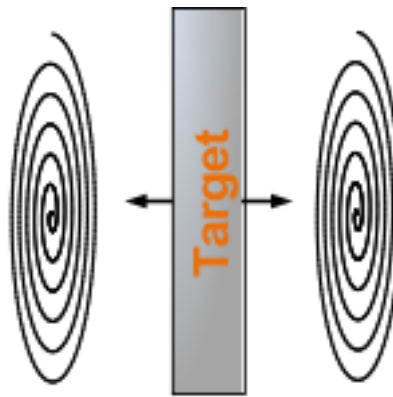
The equivalent serial resistance of the system,  $R_s$ , is a function of temperature:

$$R_s(T) = R_{s0}[1 + \alpha(T-T_0)],$$

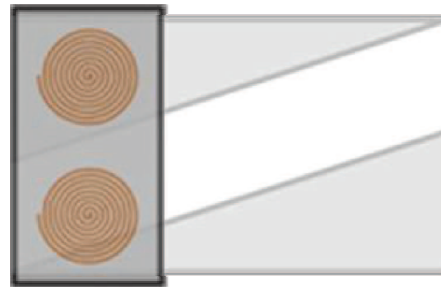
where

- $R_{s0}$  is the system resistance at temperature  $T_0$
  - $T$  is the temperature
  - $\alpha$  is the temperature coefficient of resistivity
- (6)

The system should be designed such that the outputs of the sensors depend differently on the measured parameter (distance/position/angle of the target). For example, if the position of a target is to be measured, the sensors should be located on opposite sides of it. For “slider” designs, slides should be pointed to opposing sides, and so forth.



**Figure 4. Conductive Target Position is Detected with Two Coils**



**Figure 5. Slider Position (Triangular Shapes) is Detected with Two Coils.**

It is easy to see that the ratio of the measured RP values will be temperature independent:

$$R_{P1}/R_{P2} \sim R_{S2}(T)/R_{S1}(T) = R_{S02}[1 + \alpha(T-T_0)]/R_{S01}[1 + \alpha(T-T_0)] = R_{S02}/R_{S01}$$

where

- $R_{S01}$  and  $R_{S02}$  values are temperature independent.
- (7)

Error due to temperature variation of less than 0.1% is expected with such compensation.

## 4 References

1. [http://www.engineeringtoolbox.com/linear-expansion-coefficients-d\\_95](http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95).
2. A new calculation for designing multilayer planar spiral inductors (EDN37)

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