Application Report

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LDC100x Temperature Compensation

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ABSTRACT

LDC100x 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 discusses the physical effects of temperature variation on inductive sensing and provide methods to mitigate these effects.

Contents

Trademarks

1 Introduction

The LDC100x 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 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 LDC100x. R_P is based on the following formula:

$$R_P = L / (Rs * C) \qquad (1)$$

where

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

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

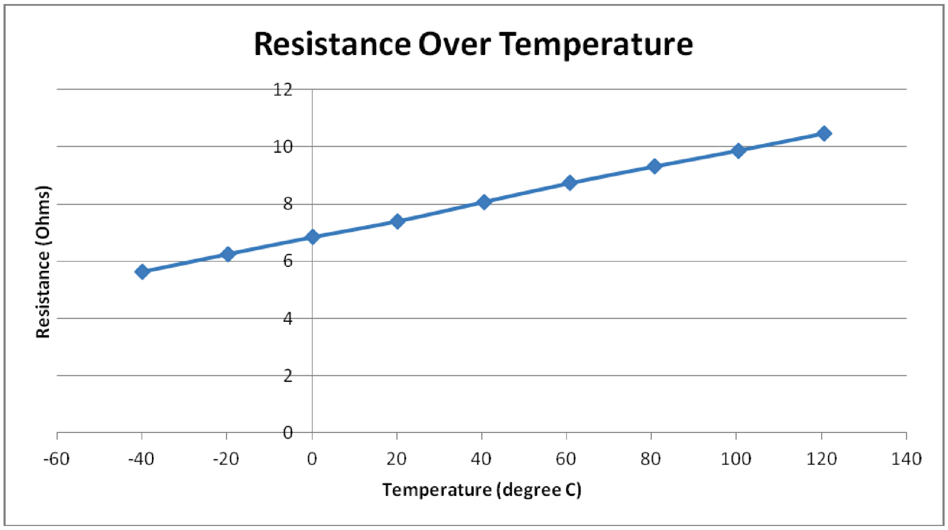

Figure 1. Resistance of a Typical PCB Coil as a Function of Temperature

The value of R_P also changes in conjunction with inductance, as described in the following paragraphs. 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. This application report considers how temperature variation affects inductance of air-core coils.

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

$$\alpha = 17\times10^{-6}/°C \text{ [1] } (17ppm/°C), \quad (2)$$

L is typically proportional to the area of the coil divided by the length of the coil. Thus, the overall variation in L is also 17 ppm/°C.

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

The inductance of a single-layer coil is proportional to the diameter of the coil [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 approximately 15 ppm/°C.

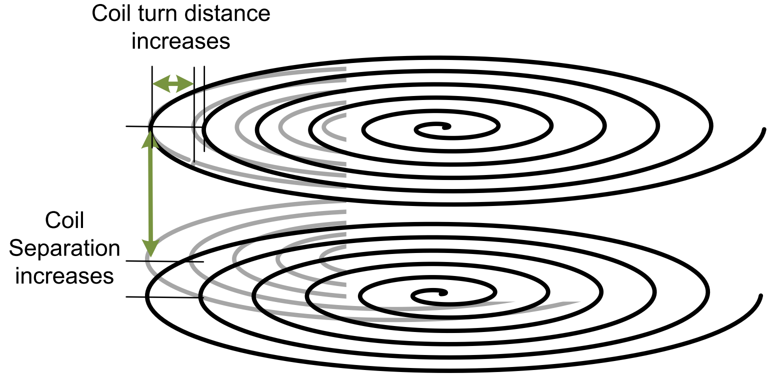

Figure 2. Multi-Layer Coil Geometry Shift Due to Temperature

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 leads to a change of the coupling between layers, the effective inductance change is actually smaller than 15 ppm/°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 changes wire resistivity, which in turn causes 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 changes resistivity, and consequently eddy current distribution in the target. This change in eddy current distribution impacts 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.

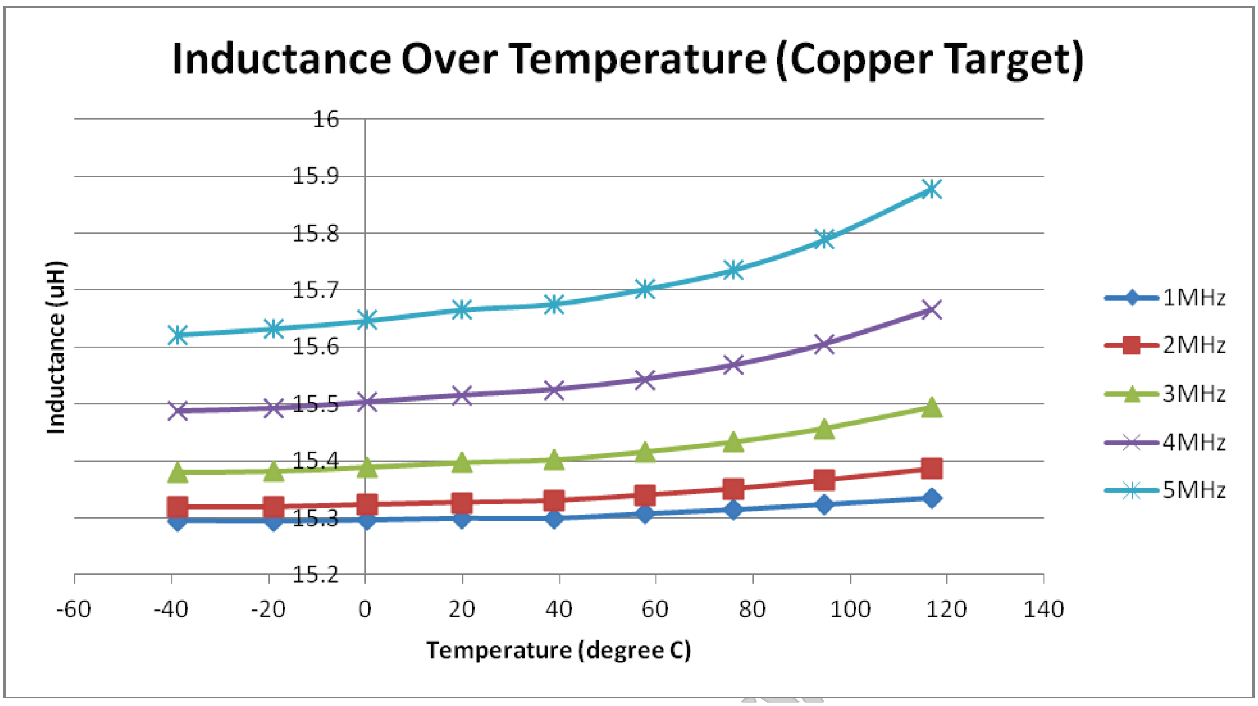

Figure 3. Inductance of a Coil as a Function of Temperature Across Frequency

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, the relative change in L ($\Delta L/L$) was equal to relative change in coil-target separation ($\Delta X/X$) divided by four. As the relative change in X may be large when X is small, care must be taken when designing mechanical system.

The LDC100x 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 30 ppm/°C temperature coefficient, are recommended. For the inductors with magnetic cores, the change in inductance over temperature is 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, this app report advises 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). This app report also assumes that the coil and target temperatures are the same.

Initial system calibration (that is, LDC100x output versus distance, position, or angle) must be recorded at controlled known temperature (25°C, for example). The LDC100x 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 data sheet.

Re-calculate calibration data to reflect R_P as a function of the parameter or parameters.

During system operation, data from the LDC100x is converted to the real R_{Pmeas} in Ohms according to the same formula, and then corrected for the temperature as follows:

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

where

- R_P is the corrected R_P value
- R_{Pmeas} is the measured R_P value
- α 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 LDC100x 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 the output must not be influenced by the varying parameter (distance, position, or 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 is no longer 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 (one-time calibration) where R_P versus parameter (distance, position, angle, and so forth) is recorded at various temperatures.

During system operation, the appropriate curve of R_P versus 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
- α is the temperature coefficient of resistivity (6)

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

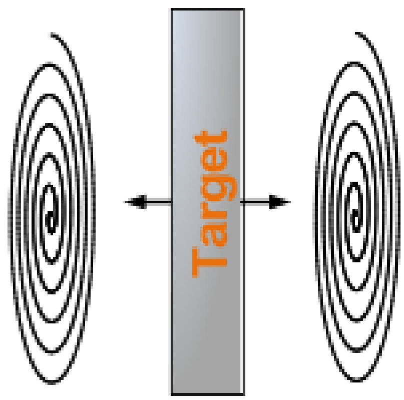

Figure 4. Conductive Target Position is Detected with Two Coils

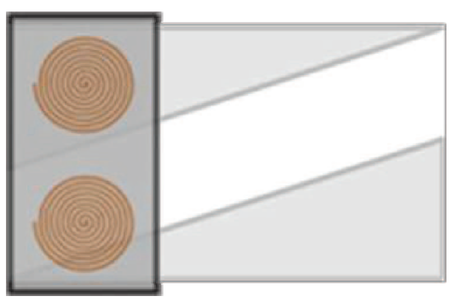

Figure 5. Slider Position (Triangular Shapes) is Detected with Two Coils

It is easy to see that the ratio of the measured RP values is 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. 1. http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.
2. 2. *A new calculation for designing multilayer planar spiral inductors* (EDN37)

Revision History

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

Changes from Original (September 2013) to A Revision	Page
• Changed LDC1000 to LDC100x throughout	1
• Updated sentence structure for clarity throughout	1