1 Background

CambridgeIC's resonant inductive position sensing technology detects the position of a moving, contactless target relative to a fixed sensor. The target comprises one or more inductors connected to resonating capacitance. The sensor comprises a number of coils, usually in the form of a printed circuit board (PCB). The sensor PCB is connected to a processor circuit, comprising CambridgeIC CTU chip and its external circuitry. The system is illustrated in the block diagram of Figure 1.

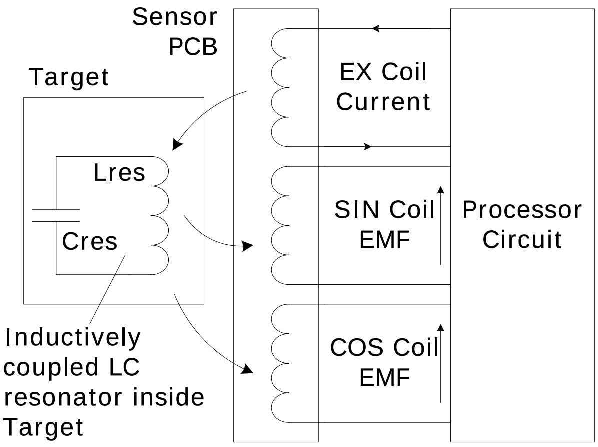

Figure 1 Block diagram

CambridgeIC processors are called "Central Tracking Units" (CTU chips) because they allow position processing to be centralised within an embedded system, usually close to a host processor. Some CTU chip variants including the CAM204 can connect to and process multiple sensors, too.

To take a measurement, the processor circuit energises the resonator inside the target with an AC current in the excitation coil, and measures the resulting signal levels induced in sensor coils. Using an electrical resonator inside the target enables much higher detected signal level than inductive sensors using metallic or ferrite targets. This delivers high measurement resolution and allows operation at big gaps between target and sensor.

To achieve high signal levels, the resonator's Q-factor must be large, so that its frequency response is narrowband. This in turn requires that the processor's excitation current is close in frequency to the target's resonant frequency.

CTU chips vary their excitation frequency to match the resonator. The frequency range is relatively broad, for example to allow for manufacturing variation of the resonator's components, and for change in frequency due to temperature change.

When designing with resonant inductive technology, it is important to check that the resonator frequency range falls within the CTU chip's tuning range. The task is usually trivial, but can be complicated when the target is physically located close to metals, when a significant frequency shift may be experienced.

This document aims to provide practical advice on testing and analysis, so the resonator's frequency range can be adequately centered on the CTU chip's frequency range.

Referenced Documents	
Part no.	**Description**
033-0003	CAM204 CTU processor chip datasheet
033-0021	CAM502 high-speed CTU processor chip datasheet

2 CTU Chip Resonator Detection

2.1 Principle of Operation

CTU chips detect a resonator inside the target as a discrete measurement process illustrated in Figure 2.

A measurement trigger starts the process, usually a “GO” request received over the SPI interface, or the expiry of an on-chip continuous timer.

The CTU chip starts by energising the resonator inside the target by passing an AC current through an excitation coil. It then turns off this excitation current, so that it does not interfere with detection. The sensor coils, typically named COS and SIN due to their spatial patterning, detect resonator signal. An EMF appears at their terminals due to the resonator. The CTU chip measures the overall signal level (Amplitude) of these signals. If Amplitude is large enough it reports Valid, and uses the COS:SIN amplitude ratio to determine position. It also determines the Resonator Frequency.

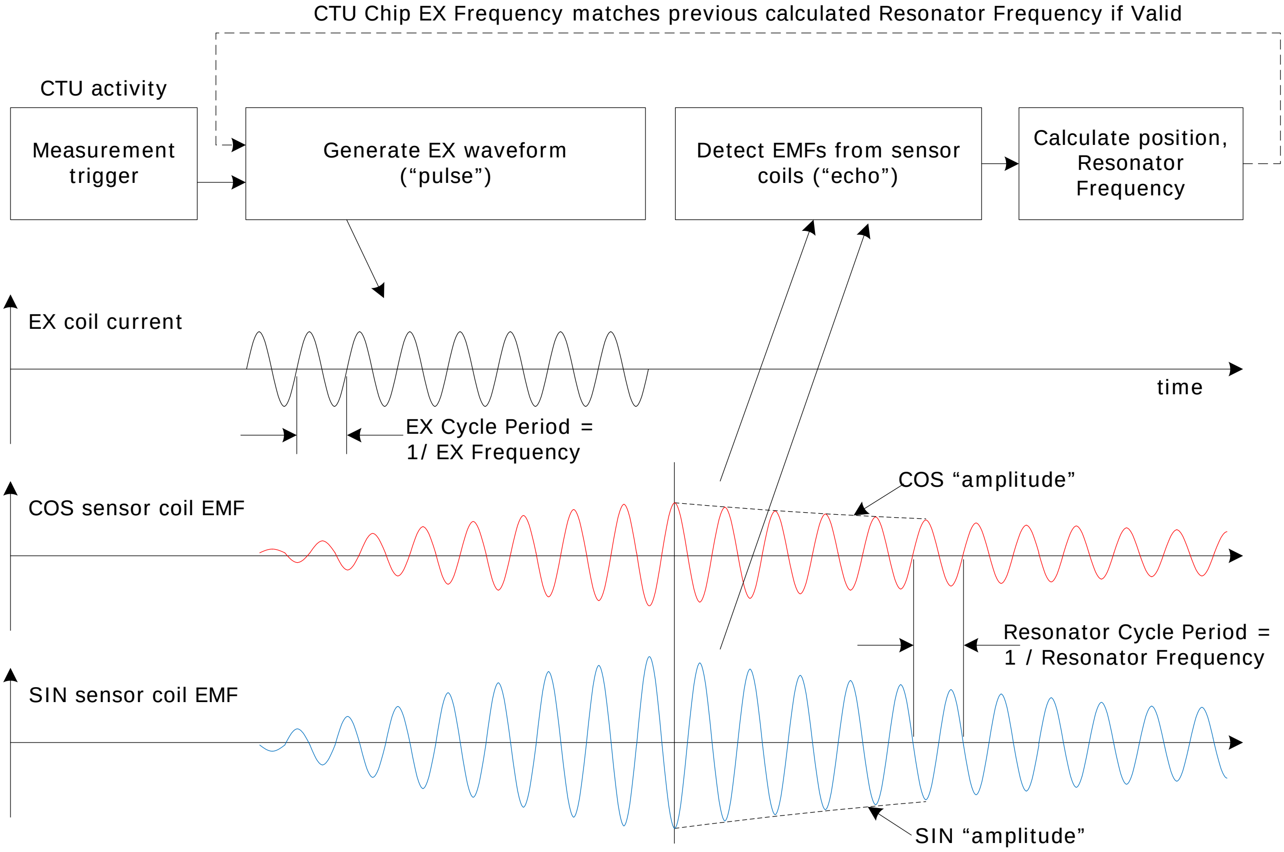

Figure 2 Resonator Excitation / Detection Process

As noted in section 1, the excitation frequency should match the resonator frequency in order to deliver the highest possible signal amplitudes and hence performance. Once a CTU chip “knows” resonator frequency from a Valid measurement, it performs the next excitation at an EX Frequency equal to the previously determined Resonator Frequency. It keeps adjusting the EX Frequency of each measurement in this way, so that changes in resonator frequency are traced over time and Amplitude is always maximised.

If there was no previous Valid measurement, for example following power up, the CTU chip performs measurements in a “search” mode. The details of the search procedure differ between CTU chips, but the objective is to deliver Valid measurements as soon as possible once a target is in range.

Some types of sensor have both coarse and fine sensor coils. Combining fine and coarse measurements helps improve resolution, particularly for rotary and longer linear sensors. CTU chips usually only detect resonator frequency using fine sensor coils, because they deliver higher signal levels by design and the measurement quality is therefore superior.

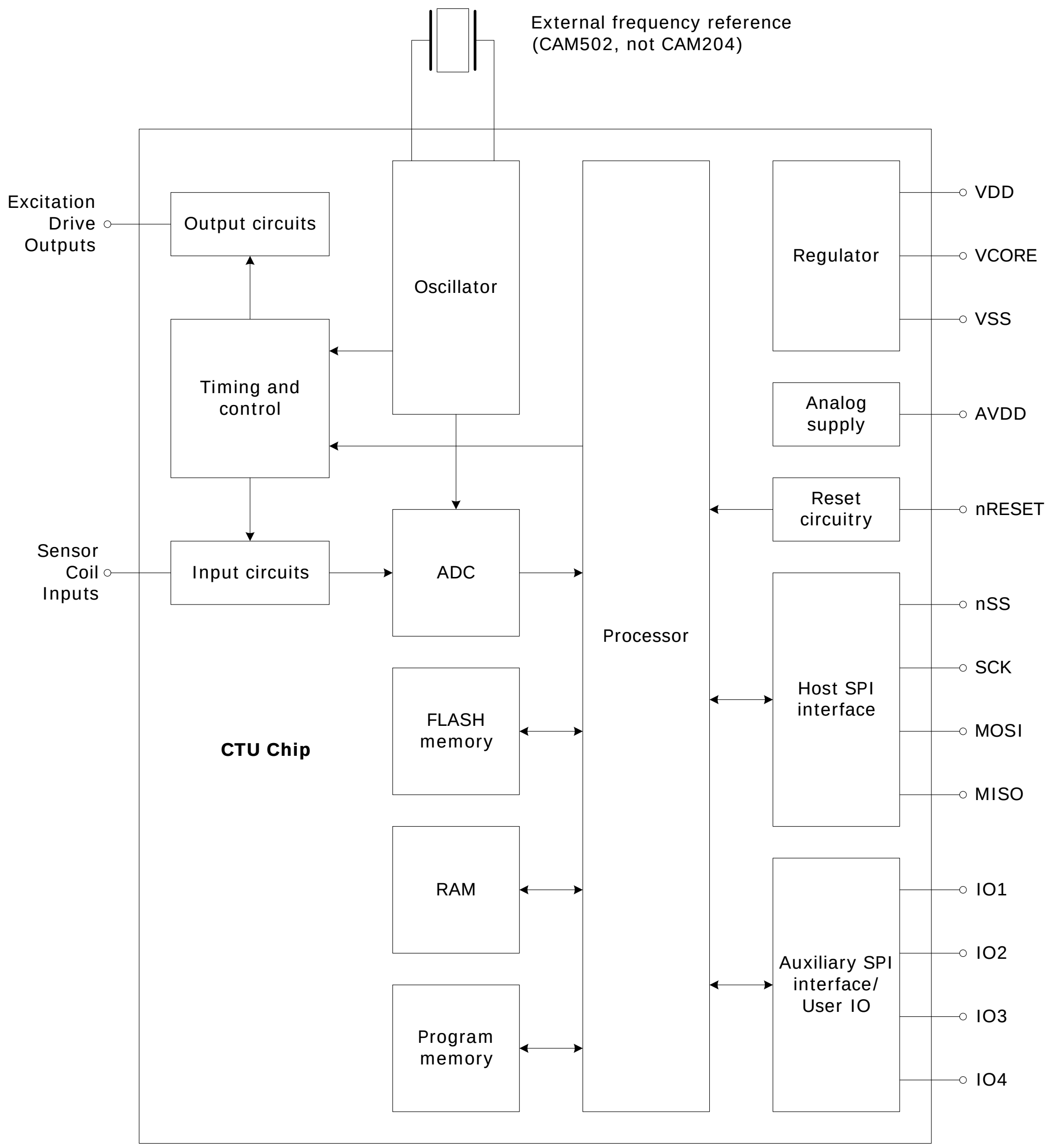

Figure 3 CTU Chip Block Diagram

Figure 3 is a general block diagram of a CTU chip. An oscillator circuit is used as a timing reference. This feeds timing and control circuitry feeding both output and input circuits.

Some CTU chips including the CAM502 use an external crystal as a frequency reference for precise timings. This enables the CTU to synchronise measurements to a host's cycle timing, for example when taking Pipeline Measurements for high speed operation. In other chips including the CAM204, the oscillator circuitry is fully internal for lower cost and smaller board footprint.

The timing and control circuitry inside the CTU chip creates the AC waveforms used to excite and detect the resonator in the target. The frequency of these waveforms is under processor control. The processor can tune the excitation and detection frequency across a certain range, to allow for system frequency tolerances.

2.2 CTU Frequency Budget

Figure 4 illustrates the CTU chip's resonator frequency tuning range, with increasing frequency shown in the upwards direction.

Each type of chip has a "Nominal CTU Operating Frequency", which is the expected frequency of the centre of its tuning range. It also has a "CTU Frequency Tolerance", which is the tolerance of the oscillator. In the case of CTU chips like the CAM204 with on-chip oscillator, the tolerance is a few percent across operating temperature range, and arises from manufacturing variability and temperature change. In the case of CTU chips with external crystal, the tolerance is that of the crystal, typically only a few hundred parts per million depending on the crystal.

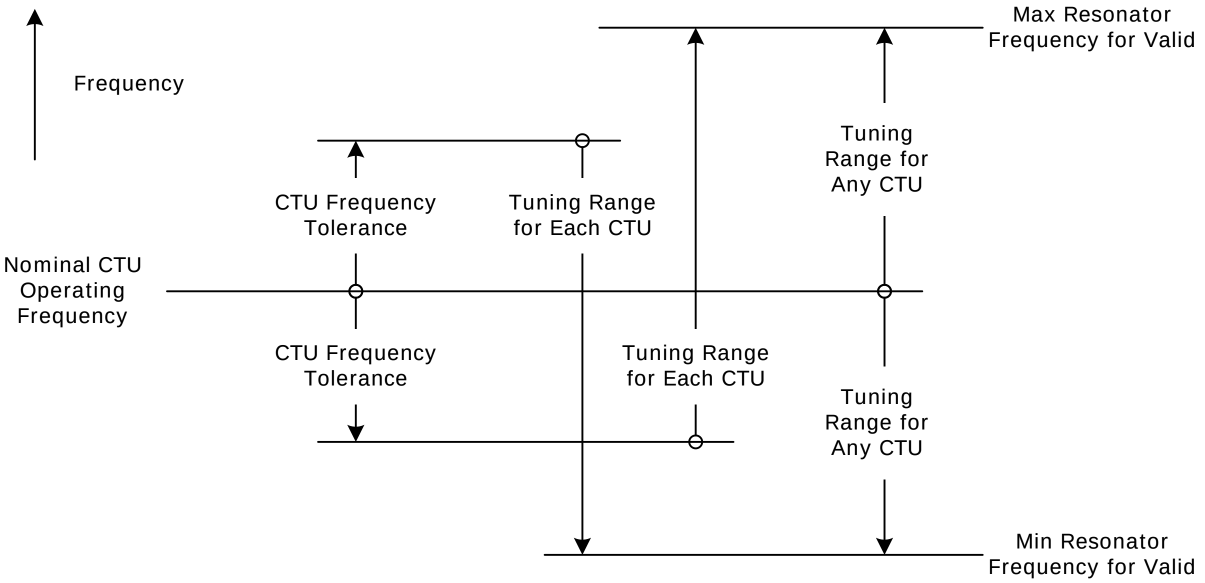

Figure 4 CTU Tuning Range

Each CTU chip is able to detect resonators with frequency within a specified "Tuning Range for Each CTU" from that CTU chip's *actual* operating frequency. That is, the chip will report Valid when its connected sensor "sees" a target with resonator frequency within that range of the *actual* operating frequency.

In most applications it is important that any randomly selected CTU chip will operate with any randomly selected resonator. There is no opportunity to pair CTU chips and resonators to ensure they work together. It is therefore important that CTU chips and resonators both conform to their own compatible frequency specifications. There must be a "Tuning Range for Any CTU", so that any CTU chip of a given type will detect a resonator across that frequency range and report Valid.

Figure 4 illustrates the relationship between the Nominal Operating Frequency, the Tuning Range for Each CTU, the Tuning Range for Any CTU, and the Maximum and Minimum Resonator Frequency for Valid.

CTU chips with on-chip and external frequency references may differ slightly in the way these figures are specified. For example the CAM502 chip's datasheet directly specifies the Maximum and Minimum Resonator Frequency for Valid, while the CAM204's specifies Tuning Range for Any CTU as a percentage deviation from Nominal CTU Operating Frequency. These may be used interchangeably using Equation 1 and Equation 2...

Equation 1

$$Maximum\ Resonator\ Frequency\ for\ Valid = Nominal\ CTU\ Operating\ Frequency \times \left(1 + \frac{Tuning\ Range\ for\ Any\ CTU}{100\%}\right)$$

Equation 2

$$Minmium\ Resonator\ Frequency\ for\ Valid = Nominal\ CTU\ Operating\ Frequency \times \left(1 - \frac{Tuning\ Range\ for\ Any\ CTU}{100\%}\right)$$

2.3 Relative Frequency Measurement Using a CTU Chip

The primary function of a CTU chip is to report the position of a target relative to a sensor, typically over an SPI interface. Multi-channel CTU chips are also available supporting multiple targets and sensors.

The CTU chip also reports diagnostic data, typically including Amplitude and Relative Frequency. Amplitude is a signal level indication, to help gauge system health.

Relative frequency is an indication of the target's resonant frequency. It is usually reported as a value in Hz. Given a value of Reported Frequency, the Actual Resonator Frequency is nominally…

Equation 3

$$\textit{Actual Resonator Frequency (Estimate)} = \textit{Nominal CTU Operating Frequency} + \textit{Reported Relative Frequency}$$

This estimate is subject to errors, in particular the CTU Frequency Tolerance, so that a better estimate is…

Equation 4

$$\begin{aligned}&\textit{Actual Resonator Frequency}\\&\quad= \textit{Nominal CTU Operating Frequency} \times \left(1 + \frac{\textit{CTU Frequency Tolerance}}{100\%}\right)\\&\quad+ \textit{Reported Relative Frequency}\end{aligned}$$

For CTU chips using an external crystal as a frequency reference, the CTU Frequency Tolerance is very small compared to other frequency tolerances in the system and can usually be ignored. In this case, Equation 3 is a good estimate of Actual Resonator Frequency.

For chips including the CAM204 with significant CTU Frequency Tolerance, Equation 3 is not sufficiently accurate to estimate Actual Resonator Frequency for design purposes, including resonant frequency centering. However it is good enough for checking change in frequency, in particular the difference between the resonator in free space and in a product's metal environment…

Equation 5

$$\begin{aligned}&\textit{Resonator Frequency Change}\\&\quad= \left(\frac{\textit{Nominal CTU Operating Frequency} + \textit{Reported Relative Frequency}}{\textit{Nominal CTU Operating Frequency} + \textit{Reported Relative Frequency}(reference)} - 1\right) \times 100\%\end{aligned}$$

For example, if a CAM204 chip (Nominal CTU Operating Frequency of 187.5kHz) reports a relative frequency of -2540 when the target is in free space (no metal nearby) and a frequency of +1940 when integrated with aluminium nearby, the change in resonator frequency is…

Equation 6

$$\textit{Resonator Frequency Change} = \left(\frac{187500 + (+1940)}{187500 + (-2540)} - 1\right) \times 100\% = 2.4\%$$

Note that Equation 5 is still an approximation because it assumes the CTU chip has Nominal CTU Operating Frequency, with zero CTU Frequency Tolerance. However the estimate is good enough for practical purposes because Reported Relative Frequency is much smaller than Nominal CTU Operating Frequency.

3 Target Design and Resonator Frequency

3.1 Target Design Options

Resonant Inductive targets may be purchased from CambridgeIC, or constructed by the customer to CambridgeIC designs.

Figure 5 illustrates CambridgeIC's Standard Target PN 013-1005. This part may be used with a number of different sensors, both linear and rotary. It is an encapsulated part, and available with a single nominal free space resonant frequency. It comprises a single ferrite rod, with winding connected to a resonating capacitor. Please see its datasheet for more details, and the datasheets of sensors for compatibility.

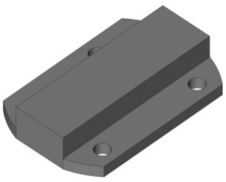

Figure 5 Standard Target PN 013-1005

Figure 6 illustrates CambridgeIC's C Target for the 35mm Type 6.3 Rotary Sensor, PN 013-1011. This part is only for use with the specific sensor. It is also an encapsulated part, available with a single nominal free space resonant frequency. It comprises two ferrite rods, with windings connected in parallel with a resonating capacitor. The two ferrite rods are on opposite sides of the rotation axis to provide immunity to misalignment between sensor and target.

Figure 6 C Target for 35mm Type 6.3 Sensor PN 013-1011

Figure 7 illustrates CambridgeIC's PCB Based C Target for the 35mm Type 6.3 Rotary Sensor, PN 013-1019. This is for use with the same sensor as the target 013-1011 above. The difference is that the wound ferrite rods are implemented using surface mountable inductors: two 20mm Transponder Coils PN 012-1704. These are mounted on a PCB, which also includes connections between the coils and a resonating capacitor, and mounting holes.

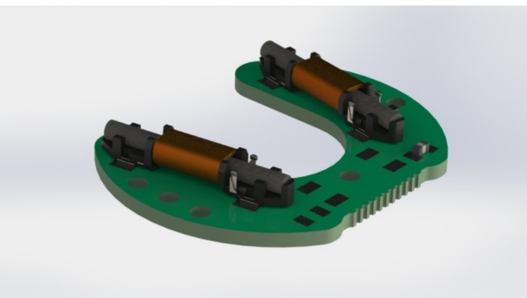

Figure 7 PCB Based C Target for 35mm Type 6.3 Sensor PN 013-1019

This PCB based target is available from CambridgeIC. Customers may also purchase the 20mm Transponder Coils from CambridgeIC, and use them to build their own targets. That way physical mounting features, PCB shape and any encapsulation can be optimised for the application. The customer may also select the values of one of more resonating capacitors to configure the part's resonant frequency to suit their application, if this requires adjustment relative to standard available values.

3.2 Frequency Calculation

Resonators inside targets can be electrically represented as an inductor connected to a capacitor as illustrated in Figure 8.

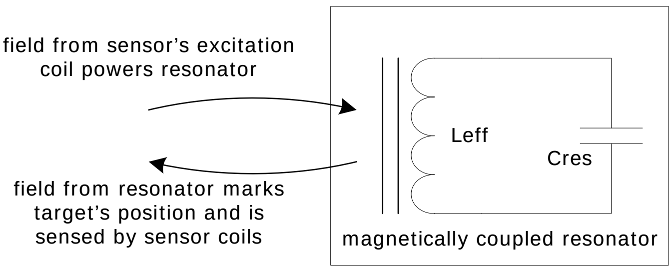

Figure 8 Basic LC resonator circuit

The inductor value Leff is the effective inductance. For a simple resonator with a single inductor in free space, this is the inductance of the inductor. For more complex targets, for example including more than one series or parallel connected inductor, Leff is the inductance of the combination. Where the target is mounted near metal, Leff is the value of inductance measured in the presence of that metal.

The capacitor value Cres is the effective capacitance in the resonant circuit. Typically this is the value of the capacitor, or the sum of two capacitors if an additional part is required in parallel to achieve a more exact nominal frequency.

The resonant frequency of the resonator is then given by…

Equation 7

$$Fres = \frac{1}{2\pi\sqrt{Leff \times Cres}}$$

To determine the capacitor value Cres to achieve a particular resonant frequency Fres given effective inductance Leff, this can be rearranged to…

Equation 8

$$Cres = \left(\frac{1}{2\pi \times Fres \times \sqrt{Leff}}\right)^2$$

3.3 Manufacturing and Temperature Tolerances

Where targets are supplied by CambridgeIC, the part's datasheet specifies manufacturing and temperature tolerances for the resonant frequency.

If the resonator is built by the customer, resonant frequency tolerances can be determined by substituting maximum and minimum values of Leff and Cres into Equation 7. Alternatively, this equation can be expressed as follows when only small changes in Leff and Cres are to be considered…

Equation 9

$$\%\ change\ in\ Fres = \frac{(\%\ change\ in\ Leff + \%\ change\ in\ Cres)}{2}$$

For example, if the inductance Lres has a manufacturing tolerance of ±2% and a temperature tolerance of ±2%, and the capacitor Cres a manufacturing tolerance of ±5% and temperature tolerance of ±0.5%, then the frequency tolerance is 0.5x(±2% + ±2% + ±5% + ±0.5%) = ±4.75%.

Tighter frequency tolerance can be achieved using tighter tolerance inductors and/or capacitors, or by testing resonant frequency of each resonator on a production line and rejecting (or adjusting) those with tolerance outside a desired specification. This test is usually applied at room temperature, so the actual resonator frequency will be subject to additional change in use due to temperature.

3.4 Influence of Metal on Resonator

When the sensor and target are mounted near metal, signal Amplitude tends to decrease and frequency tends to increase. Figures are presented in the sensor and/or target's datasheet, or may be established by experiment. This section describes the effects in general, as background for the next section.

Figure 9 illustrates how Amplitude changes with the proximity of metal, in general. As metal nears the sensor and/or target, Amplitude decreases, and hence system performance including resolution and reproducibility. The decrease is a great deal more for steel and stainless steel than for aluminium or copper, because steels have much higher resistance and therefore lose more energy in eddy currents. For this reason, it is recommended to avoid steel very close to the sensor and target. If steel is unavoidable then it is usually best to position an aluminium screening plate between the steel and sensor/target, so that the sensor and target "see" aluminium rather than steel.

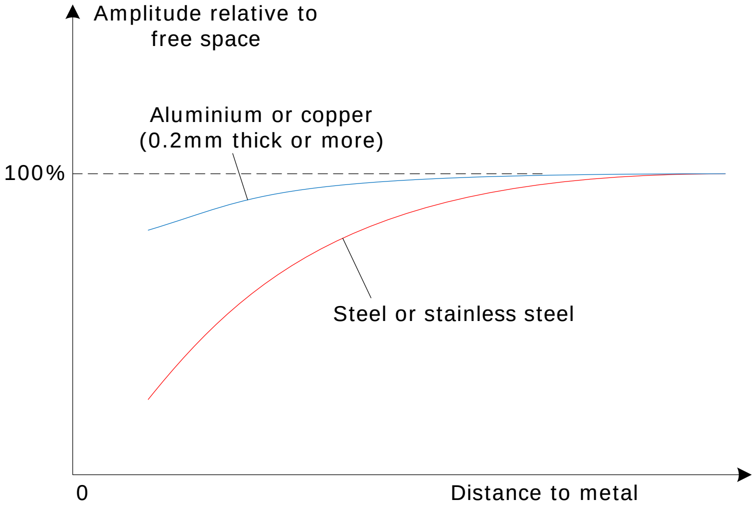

Figure 9 Influence of metal on Amplitude

Aluminium and copper do, however, affect resonant frequency of the target much more than steel, because they tend to repel and hence confine the magnetic fields, reducing the self-inductance of coils. This effect is illustrated in Figure 10.

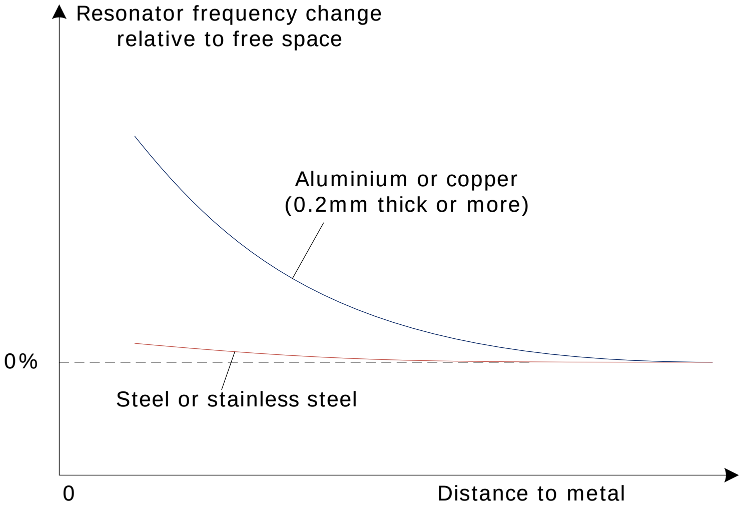

Figure 10 Influence of metal on resonator frequency

When designing a sensor into a product that includes metals near the sensor and target, the effects of that metal on Amplitude and frequency should be checked. The effects are highly reproducible across units.

The first task is to determine how much Amplitude and frequency change by in the presence of the product's metal. Figures may be available in the datasheets for the sensor and/or target. Or the change may be established by experiment, for example by using a CTU chip connected to the sensor to check the percentage change in frequency between free space and in the product's metal environment.

Next, the effects of those Amplitude and frequency changes should be checked.

In the case of a reduction in Amplitude, the main effect is a loss of noise free resolution. As a general guide, noise free resolution reduces by 1 bit (twice as much position noise) when Amplitude halves. In extreme cases Amplitude may be so low that the CTU chip is unable to reliably detect the target. Please refer to the resonator detection section of the relevant CTU chip datasheet for figures. The figures presented are for absolute minimum Amplitude, and it is recommended that typical working Amplitude be at least twice this figure to allow for system tolerances and temperature change.

A change in resonator frequency does not affect system performance significantly, providing the resonator frequency remains within the tuning range of the CTU chip, as detailed in section 2.2. The remainder of this section explains how to check resonator frequency is OK, and the steps to take to modify resonator frequency if required.

3.5 Checking Resonator Frequency

The previous section 3.3 illustrated how metal near the target and sensor may cause a change in resonator frequency. This is illustrated in Figure 11, which expresses the relationship...

Equation 10

$$\begin{aligned}&\mathit{Nominal\ Resonator\ Frequency\ in\ Metal\ Environment}\\&\qquad = \mathit{Nominal\ Resonator\ Frequency\ in\ Free\ Space} + \mathit{Resonator\ Frequency\ Change\ due\ to\ Metal}\end{aligned}$$

If there is no significant metal near the sensor and target then the Nominal Resonator Frequency in Metal Environment equals the Nominal Resonator Frequency in Free Space.

Section 3.4 described the origin of Manufacturing and Temperature Tolerances. These are in addition to the Nominal Resonator Frequency in the Metal Environment, so that...

Equation 11

$$\begin{aligned}&\mathit{Maximum\ Resonator\ Frequency\ in\ Metal\ Enviroment}\\&\qquad = \mathit{Nominal\ Resonator\ Frequency\ in\ Metal\ Environment}\\&\qquad + \mathit{Manufacturing\ and\ Temperature\ Tolerance}\end{aligned}$$

Equation 12

$$\begin{aligned}&\mathit{Minimum\ Resonator\ Frequency\ in\ Metal\ Enviroment}\\&\qquad = \mathit{Nominal\ Resonator\ Frequency\ in\ Metal\ Environment}\\&\qquad - \mathit{Manufacturing\ and\ Temperature\ Tolerance}\end{aligned}$$

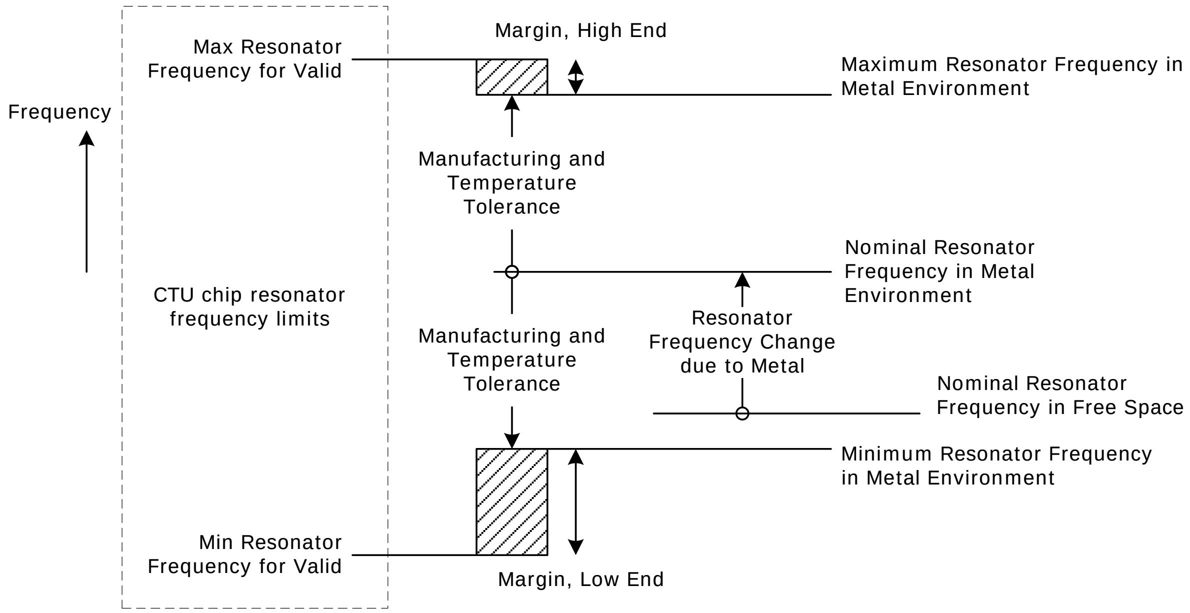

Figure 11 Checking that resonator frequency range is inside CTU frequency range

For the system to operate reliably across manufacturing and temperature variations, the resulting Maximum and Minimum Resonator Frequency in the Metal Environment must fall within the CTU chip's Maximum and Minimum Resonator Frequency for Valid, as illustrated in Figure 11.

Figure 11 illustrates the frequency margins at the high and low frequency end. It is sufficient that both margins are greater than zero. That is, the Maximum Resonator Frequency in the Metal Environment must be less than the Maximum Resonator Frequency for Valid, and the Minimum Resonator Frequency in the Metal Environment must be greater than the Minimum Resonator Frequency for Valid. However where design flexibility allows, the two margins should be equal, so that design margin is maximised.

3.6 Modifying Resonator Frequency

If there is insufficient margin at one end of the frequency range, and where the target design allows it, the resonator's free space frequency may be modified. This is usually done by changing the value of the resonating capacitance, Cres of Figure 8. The capacitor or capacitors may be changed to new values, or an additional capacitance added in parallel with existing capacitors. Please refer to section 3.2 for frequency and capacitor value calculation.

Some types of target are available from CambridgeIC with different free space resonant frequency values to suit different metal environments. In this case the suitability of each frequency variant may be assessed, to help select the one yielding the greatest frequency margin.

If there is insufficient margin at both ends of the frequency range then the Manufacturing and Temperature Tolerance is excessive. It may be necessary to select tighter tolerance capacitor(s), or to perform a test on resonant frequency at manufacture against tighter frequency limits, to guard against extreme combinations of inductor and capacitor tolerance.

3.7 Resonator Capacitor Specification

When selecting resonating capacitors for targets, the following should be considered:

- Capacitors must have a usable tolerance, ideally ±5% or better.
- Capacitors must have adequate voltage rating for the sensor application. Please refer the relevant sensor/target datasheet. In general the required rating will be at least 100V, and usually 200V or more.
- Capacitors must be low-loss types, typically NPO/COG dielectric.
- Capacitors are available in standard values, and it may be necessary to use a parallel combination of two capacitors C1 and C2 to achieve a desired resonator capacitance Cres = C1 + C2. Try combinations of different standard values to find the best match. It is unlikely that more than two capacitors will be required to achieve a particular Cres value to adequate precision.
- Series combinations of capacitors should be avoided because this generally yields low Q-factor due to high series resistance.

3.8 Further Assistance

This document is intended to provide background and guidance, and may allow some customers to perform their own development with little or no assistance. However CambridgeIC's engineers remain on hand should any design-in assistance be required, and to help customers check their integration.

4 Document History

Revision	Date	Description
0001	5 February 2016	First draft

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6 Legal