1 Introduction

1.1 Background

CambridgeIC's Type B sensors detect the position of a moving, contactless target using resonant inductive sensing. The Resonant Inductive Encoder IC circuitry drives an excitation coil to emit a "pulse". The coupling between the excitation coil and the target causes the target to resonate in response to the pulse. After the pulse ends, multiple sensing coils are used to detect the "echo" as the target resonator decays. The Resonant Inductive Encoder IC processes their signals to yield accurate information about the position and velocity of the target, along with information relevant to system health. All necessary processing of the pulse-echo process is managed by the Resonant Inductive Encoder IC circuitry. This circuitry delivers position, velocity and diagnostic data to a host system over a suitable interface.

Figure 1 shows a typical example of the system. The sensor PCB houses the excitation and sensing coils. The target PCB includes a printed resonator coil and capacitors that form a resonant circuit.

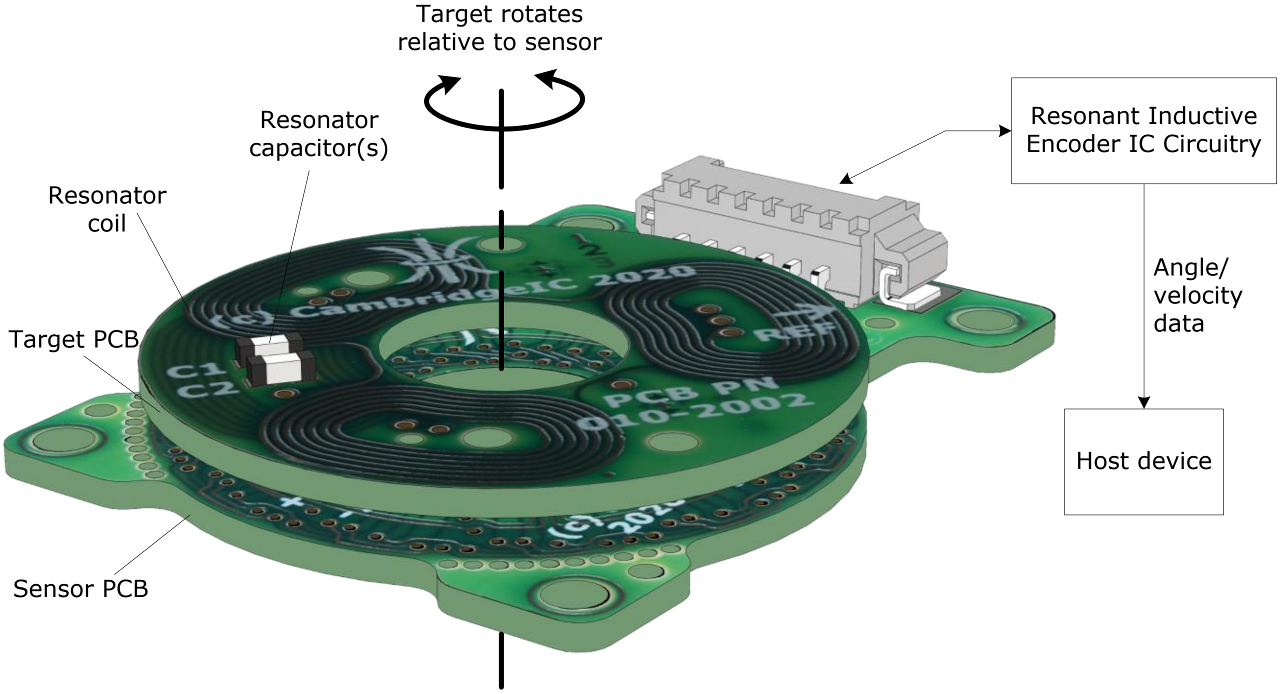

Figure 1 System block diagram

1.2 Purpose

CambridgeIC makes sensor and target designs available to customers, so they can embed them inside their own products. This Reference Manual is to assist customers with the design and integration of sensors and targets.

1.3 Audience

This document is intended for a customer's electronic and mechanical designers.

1.4 Related Documents

For details specific to a particular sensor and target design, please refer to the sensor's datasheet. This includes mechanical drawings and performance data. 3D CAD data for sensor and targets is also available from CambridgeIC.

For details of Resonant Inductive Encoder ICs and their circuitry, please refer to the relevant IC datasheet.

2 Principle of Operation

2.1 Equivalent Circuit

Sensors and targets are both built using a conventional PCB process and include shaped coils designed by CambridgeIC. Typical arrangements are illustrated in Figure 2.

The target also includes a resonator capacitance CRES. This is typically formed by two capacitors connected in parallel, as shown in Figure 1. CRES is connected to the target's printed resonator coil LRES. This forms an LC resonant circuit. Using a resonant circuit greatly improves achievable signal levels, and means that the system can operate well with big gaps between the sensor and target, while still delivering high accuracy and resolution.

The sensor includes an excitation coil (EX) for powering the target's resonator. Coupling between the excitation and resonator coils is uniform with angle, so that the resonator is powered irrespective of position.

The remaining coils are used to detect the resonator's AC magnetic field.

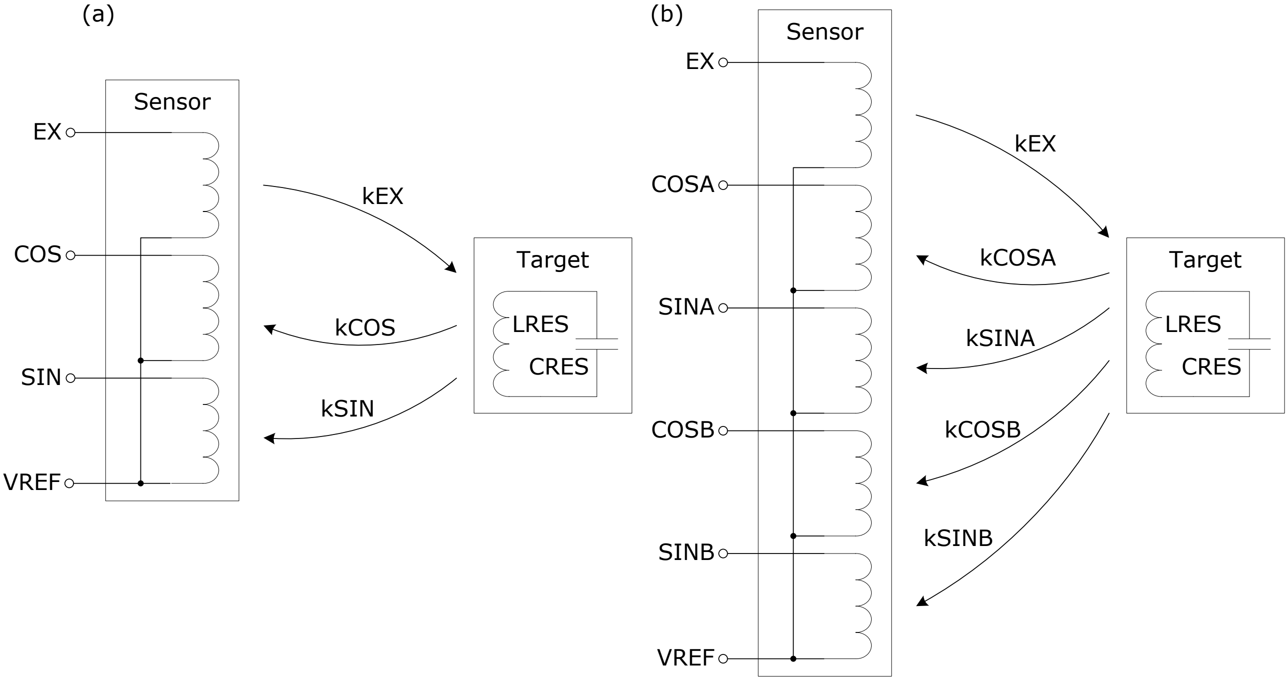

Figure 2 Equivalent circuits, (a) basic and (b) precision sensors

Figure 2(a) illustrates a sensor with 3 coils: EX, COS and SIN. This is a "basic" sensor arrangement. Figure 2(b) illustrates a sensor with 5 coils: EX, COSA, SINA, COSB and SINB. This is a "precision" sensor arrangement.

The resonator and sensor coils are specially patterned so that the coupling factors between them vary in a precise way with position. The next section explains the relationship between coupling factors and position, and the difference between a basic and precision sensor.

2.2 Coupling Variation with Position

Figure 3 illustrates how the coupling factors between a basic sensor's COS and SIN coils and its resonator coil vary with position x. The two coupling factors vary sinusoidally in phase quadrature. The peak coupling factor depends mainly on the gap between sensor and target.

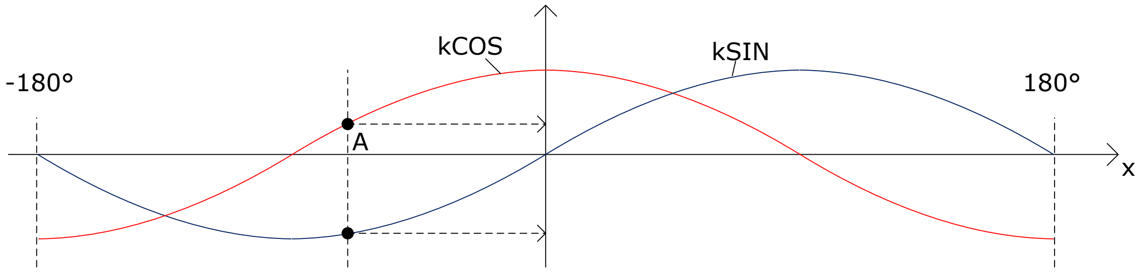

Figure 3 Variation of coupling to resonator with angular position, basic sensor

Figure 4(a) illustrates how the coupling factors between a precision sensor's "coarse" COSB and SINB coils and its resonator coil vary with position x. Note that the relationship is the same as for a basic sensor illustrated above. These coarse coils are used to determine absolute position across the measuring range, usually 360°.

Figure 4(b) illustrates how the coupling factors between a precision sensor's "fine" COSA and SINA coils and its resonator coil vary with position x. The two coupling factors vary sinusoidally in phase quadrature, and they repeat multiple times along the measuring range. These fine coils are used to determine precise position across the measuring range. To determine precise, full absolute position across 360°, the processor IC combines the absolute position information from coarse coils and the precise position information for the fine coils.

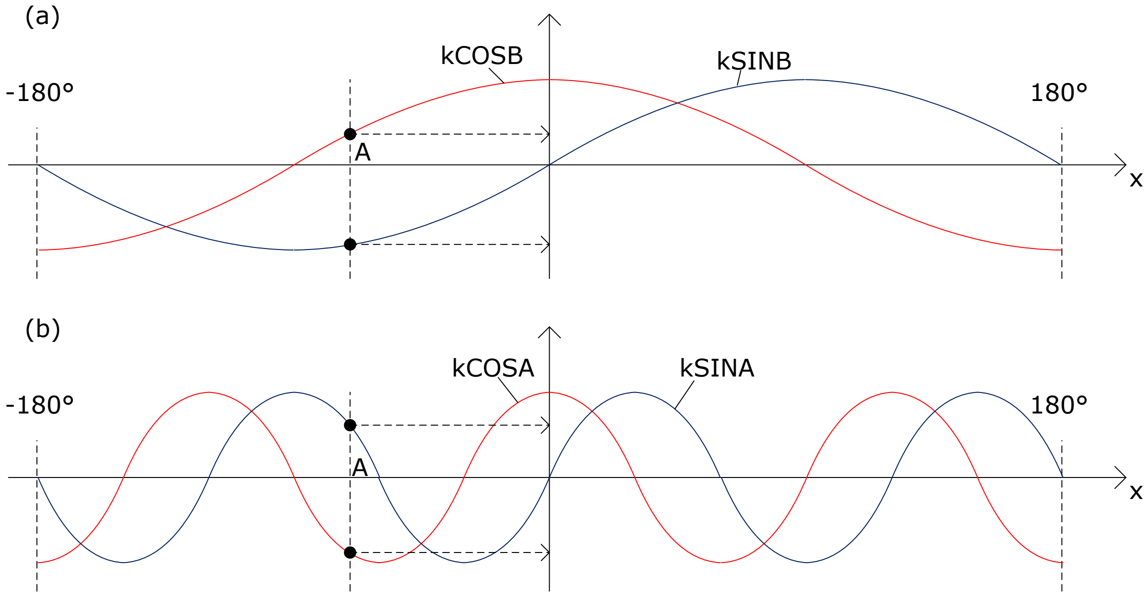

Figure 4 Variation of coupling to resonator with angular position, precision sensor

A Precision sensor's Subtype is the number of fine coil COSA,SINA repeats for every coarse coil COSB,SINB repeat. For example Figure 3 illustrates a sensor system with Subtype=3. The Subype for basic sensors is 0. Subtype is a configurable setting inside the Resonant Inductive Encoder IC. It must be configured to the correct value for the connected sensor in order for the system to function correctly.

The Resonant Inductive Encoder IC does not directly determine coupling factors. Instead, it measures the signal levels that the resonator induces in each sensor coil, integrated across a Detection Period as described in section 3.3. The measurements taken by the Resonant Inductive Encoder IC are denoted ACOS, ASIN and so on below. These differ from the coupling factors kCOS and kSIN only by a scaling factor. Position calculation is ratiometric, see section 2.3. This means that the scaling factor does not affect the position measurement result.

2.3 Basic Position Calculation

Since they vary sinusoidally and in phase quadrature with position x, the Resonant Inductive Encoder IC's measurement of signal levels (ACOS,ASIN) forms a vector whose angle marked x in Figure 5 is equal to the target's position. This angle may be obtained by taking a 4-quadrant inverse tangent ("atan2") of the two coupling factors. This calculation is done inside the Resonant Inductive Encoder IC.

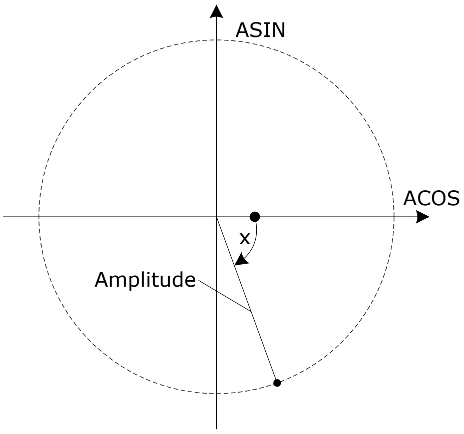

Figure 5 Position calculation, basic sensor

The magnitude of the (ACOS,ASIN) vector is known as Amplitude, and is reported by the Resonant Inductive Encoder IC over its debug interface.

2.4 Effect of Noise and Amplitude

Figure 6(a) illustrates the calculation of position x from ACOS and ASIN measurements like in Figure 5. This time measurement noise ΔN is included. Noise disturbs both ACOS measurements (variability in the left-right direction) and ASIN measurements (variability in the up-down direction). Together these disturbances tend to move the locus of the (ACOS,ASIN) vector in a circle around its ideal position. The system's measurement of position x is disturbed by an amount Δx.

Figure 6(b) illustrates the calculation of position x from ACOS and ASIN measurements when Amplitude is smaller. Most noise sources including random noise tend to be constant and do not change with Amplitude, so ΔN is the same as in Figure 6(a). The effect is to increase the variability in reported position Δx when Amplitude is smaller.

Low Amplitude therefore causes more variability in reported position x due to noise. Higher noise means lower resolution. This is the origin of the equation for Expected Noise Free Resolution, Equation 15.

Note however that the average reported position does not change with Amplitude; the calculation of position x is ratiometric. Since Amplitude varies with gap, temperature and other things, this makes the processor's calculation of position insensitive to all those variables too.

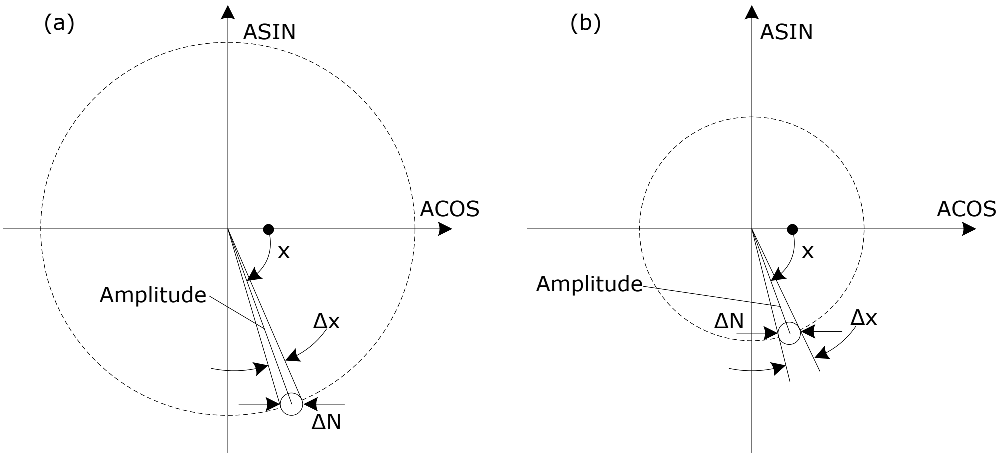

Figure 6 Position calculation, effect of Amplitude and measurement noise

2.5 Precision Position Calculation

When processing a precision sensor, the Resonant Inductive Encoder IC calculates position using both fine and coarse coil pairs. The fine coil measurements (ACOSA,ASINA) are used to determine fine position, which repeats multiple times around 360° and is therefore ambiguous. The coarse coil measurements (ACOSB,ASINB) are used to determine coarse position, which is absolute around 360° but suffers from much greater errors. Fine and coarse position calculations are both done in the same way as for a basic sensor, described in section 2.3.

The Resonant Inductive Encoder IC combines both position measurements and reports full absolute position to the host. This has high accuracy and resolution coming from the fine measurement, and is made absolute by the coarse measurement.

Once a first coarse measurement has been taken, it is repeated only very occasionally. The Resonant Inductive Encoder IC can keep track of absolute position by counting fine repeats, even at extreme rotation speeds.

2.6 Excitation and Detection

Sections 2.2 and 2.3 described how signal measurements from sensor coils vary with position, and how that variation is used to determine position.

The measurement of sensor coil signal levels is done using a Pulse Echo measurement approach. The Resonant Inductive Encoder IC circuitry drives an alternating excitation current into the EX coil. It adjusts the frequency of this current to match the resonant frequency of the resonator in the target. Several cycles are used to excite the resonator for efficiency. The excitation current is then removed. The resonator's oscillation continues and decays slowly with time – the "echo".

This "echo" is then detected by the sensor coils. The Resonant Inductive Encoder IC detects the amplitudes of signals in each coil. This detection process is done at an appropriate electrical phase, so as to distinguish positive from negative amplitude values.

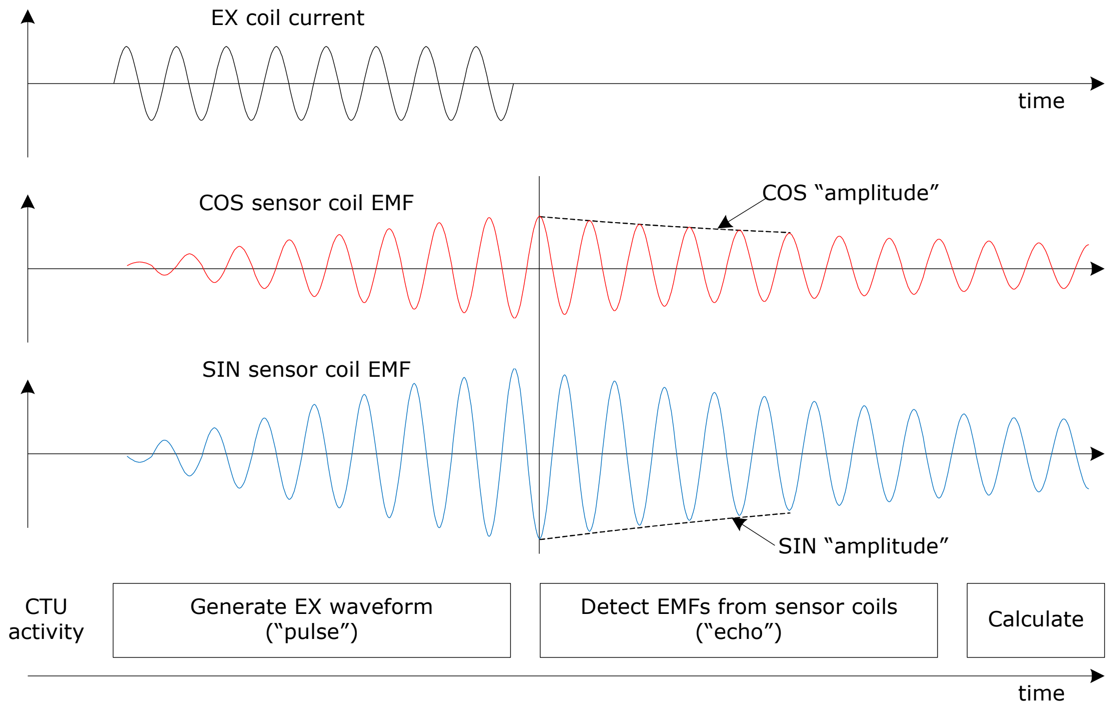

Figure 7 Pulse Echo measurement process

3 Resonator Principles and Measurements

3.1 Decay Equations

Figure 8 shows how the resonator EMF in a sensor coil E(t) decays with time.

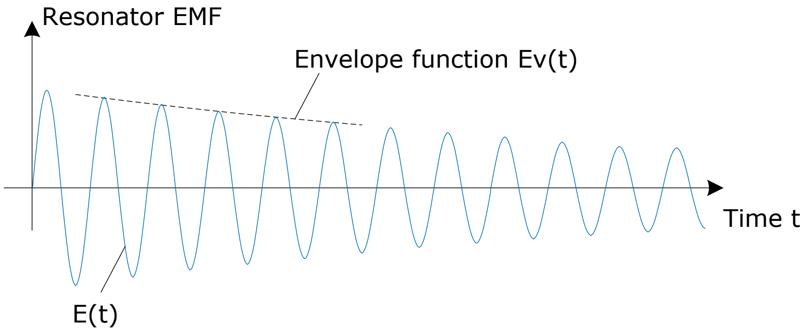

Figure 8 Decaying resonator EMF measured in sensor coil

This decaying waveform can be described as a continuous sinusoidal waveform multiplied by an envelope function as in Equation 1.

Equation 1

$$E(t) = Ev(t) \times sin[2\pi \times Fres \times t + P0]$$

The sinusoidal part of this equation is described by the parameters Fres and P0. Fres is the resonant frequency of the target's resonator and P0 is a phase offset which is roughly constant for a given sensor and target.

The envelope part Ev(t) is an exponential decay given by Equation 2.

Equation 2

$$Ev(t) = Ev0 \times e^{\frac{-\pi \times Fres \times t}{Q}}$$

Fres is the resonant frequency of the target's resonator as before. Ev0 is a starting value at t=0. Q is the Q-factor ("quality factor") of the resonator. Q and Q-Factor are used interchangeably in this document.

Equation 2 can be expressed in terms of the number of AC cycles N in place of (Fres x t), see Equation 3.

Equation 3

$$Ev(N) = Ev0 \times e^{\frac{-\pi \times N}{Q}}$$

This can be used to find the value of Q, given an oscilloscope waveform of the resonator waveform looking like Figure 8. Find the number of resonator cycles N between a start point and the point at which the waveform's envelope has decayed by 1/e (0.37 times its value at the start point). The Q-factor is then given by Equation 4.

Equation 4

$$\frac{Ev(N)}{Ev0} = 0.37 \rightarrow Q = \pi \times N$$

3.2 Resonant Frequency Equations

The target's resonator comprises a printed coil with inductance LRES and tuning capacitance CRES. CRES is formed by one or more tuning capacitors connected in parallel. Ignoring the small influence of Q-Factor, resonant frequency is given by Equation 5.

Equation 5

$$Fres = \frac{1}{2\pi\sqrt{CRES \times LRES}}$$

It is also helpful to express how small changes in capacitance CRES and inductance LRES influence resonant frequency Fres, see Equation 6.

Equation 6

$$\frac{\Delta Fres}{Fres} = -0.5 \times \left[\frac{\Delta CRES}{CRES} + \frac{\Delta LRES}{LRES}\right]$$

For example, if CRES is increased by 2% (ΔCRES/CRES=0.02), Fres will decrease by 1% (ΔFres/Fres=-0.01).

Similarly, if LRES is reduced by 0.4% ((ΔCRES/CRES=-0.004), Fres will increase by 0.2% (ΔFres/Fres=0.002).

3.3 Importance of Q-Factor

High Q-Factor is important for system performance. It yields high Amplitude, and there is a direct relationship between high Amplitude and high noise free resolution (Equation 15).

Figure 9 illustrates the EMF in a sensor coil induced by the resonator. In Figure 9(a) the resonator's Q-Factor is high, so that the resonance decays slowly. In Figure 9(b) the Q-Factor is somewhat lower, so that EMF decays faster. The Resonant Inductive Encoder IC detects the sensor coil EMF across a fixed Detection Period equal to several AC cycles. The detection process effectively integrates the EMF envelope, which is equivalent to the area of the shaded areas shown. When Q-Factor is low, the shaded area is much smaller. This is what leads to lower signal amplitude and hence lower resolution.

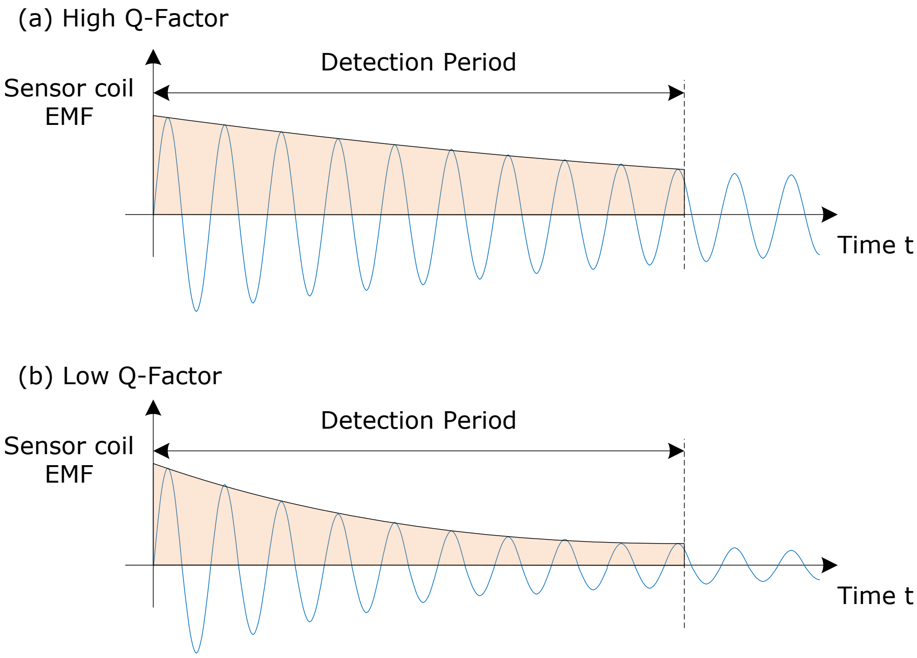

Figure 9 Effect of Q-Factor on detection

The Resonant Inductive Encoder IC also measures the frequency of the resonator signals in sensor coils. This measurement is used to control the excitation frequency, so that it matches the resonator frequency for maximum operating efficiency. The frequency measurement process may become unreliable when Q-Factor is very low. The Resonant Inductive Encoder IC's datasheet therefore specifies a minimum allowable Q-Factor for the target's resonant circuit for reliable operation.

The Resonant Inductive Encoder IC's datasheet also specifies a maximum allowable Q-Factor for the target's resonant circuit. This is to ensure that the resonator decays by a sufficient amount between measurements, so that resonator signal from one measurement does not influence the result from the next one to an excessive extent. This limit is not normally encountered when using CambridgeIC's printed target designs.

3.4 Origin of Q-Factor

A resonator's decay is the result of energy loss. The main loss mechanisms are the AC resistance of the resonator coil RL, energy loss due to coupling to any nearby metal, energy loss to the sensor and the resistance of the capacitor RC. These are illustrated in Figure 10(a).

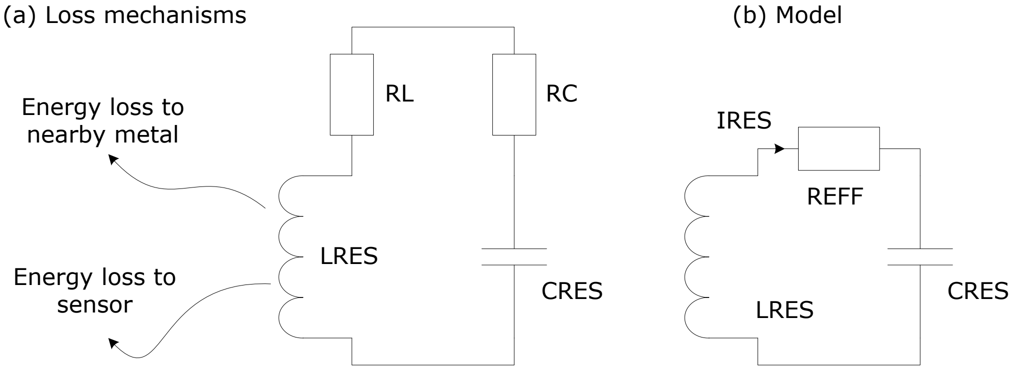

Figure 10 (a) Loss mechanisms and (b) model using effective resistance

Energy is lost to the sensor, especially when the gap between sensor and target is small. This energy loss mainly occurs during excitation, due to coupling back from the resonator to the excitation coil and resistive losses in the excitation coil. The Resonant Inductive Encoder IC's drive circuitry is switched to a higher impedance state during detection, so its influence on Q-factor during the important detection period is much lower.

It is often convenient to model resonator energy losses into an effective resistance REFF, as shown in Figure 10(b). AC current flowing in the resonant circuit is denoted IRES. This current induces EMFs in the sensor coils, so its amplitude should be maximised. Note that for a given value of resonator current IRES, energy loss is minimised when REFF is minimised. The value of REFF is the effective series resistance of each source of energy loss, as expressed in Equation 7.

Equation 7

$$REFF = RL + RC + RENVIRONMENT$$

RENVIRONMENT models energy loss to the resonator's environment including to nearby metal, the sensor and any screening material. Note that the effect of RENVIRONMENT is always to increase REFF relative to the free space value (RL + RC), and hence always to increase losses and reduce Q-Factor.

Providing the capacitor is chosen for low loss, usually with a NPO/COG dielectric, the value of CRES is usually insignificant compared to RL and may be ignored. In a free space environment where RENVIRONMENT=0, the lowest achievable loss and hence the highest achievable Q-Factor will depend on minimising the AC resistance of the resonator coil.

The resonator's Q-Factor may be calculated from Equation 8.

Equation 8

$$Q = \frac{2\pi \times Fres \times LRES}{REFF}$$

3.5 Frequency Measurement with an Oscilloscope

The target's resonator frequency and Q-factor may be directly measured using an oscilloscope connected to Resonant Inductive Encoder IC circuitry.

Figure 11 illustrates the measurement of resonator frequency. The oscilloscope is triggered by the Resonant Inductive Encoder IC's DR2 output (blue trace, labelled 2). This is high during excitation and goes low just before its end. Its DR1 output is also shown (yellow trace, labelled 1). This toggles at the excitation frequency during excitation, and is used to control half bridge MOSFET circuitry that generates excitation current. The resonator signal is measured at the sensor's COSA output, with the oscilloscope set to AC coupling (green trace, labelled 4). The resonator's position has been adjusted to maximise COSA signal. It is also possible to measure SINA instead, if its signal level is greater and it is desirable not to move the target.

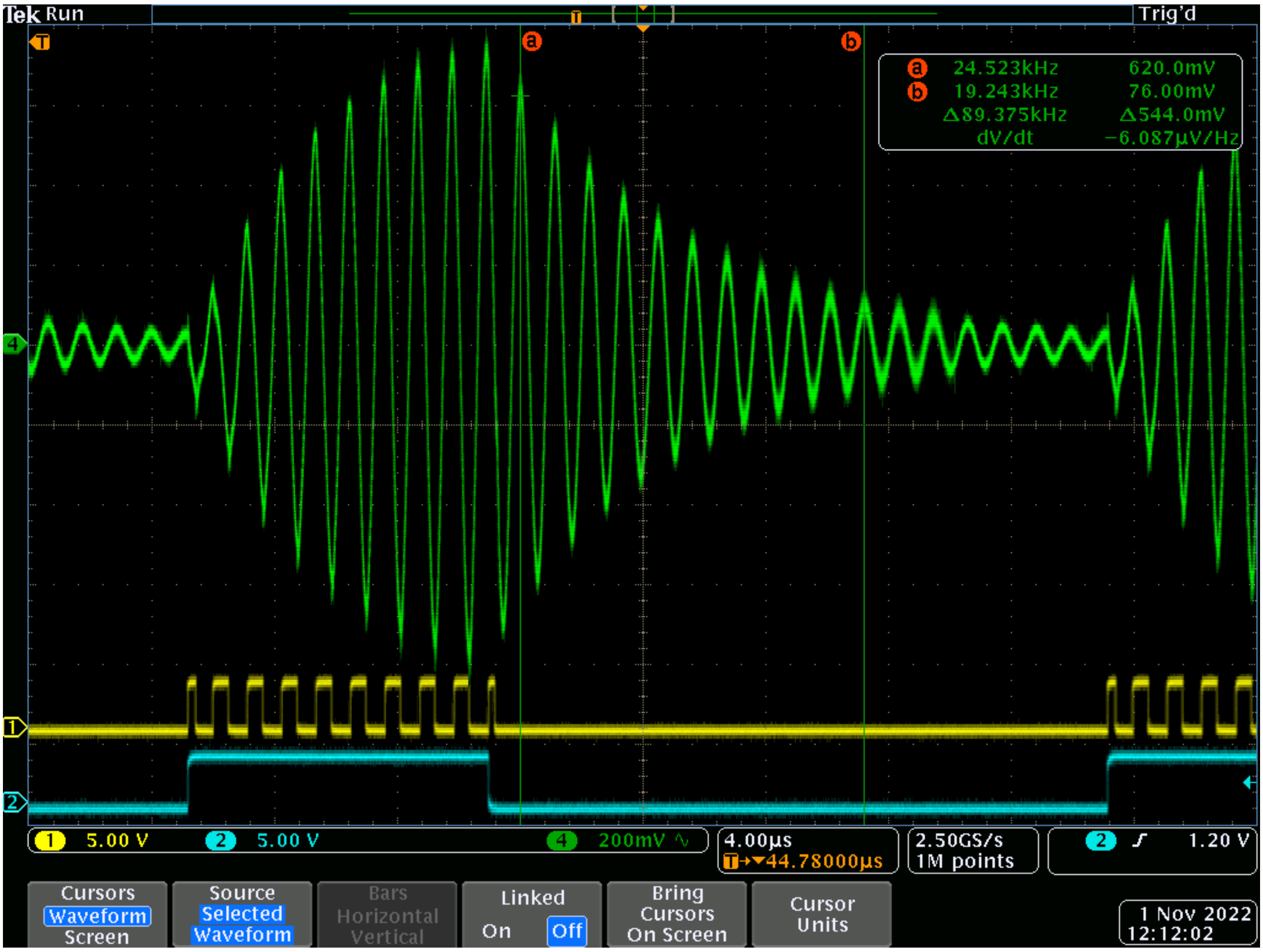

Figure 11 Resonator frequency measurement

The oscilloscope's vertical cursors have been set to measure the frequency of the resonator during the decay period. The left hand cursor a is positioned as close to the excitation as possible while maintaining at least half a resonator cycle after the final edge on DR2. This is to maximise signal level while avoiding any influence of excitation. The right hand cursor b is positioned at the same point on the resonator waveform (the peak value in this case) several cycles later (10 in this case). The separation between cursors should be maximised across the oscilloscope screen to obtain best measurement accuracy, while avoiding the following excitation period shown to the right where DR2 goes high again. The oscilloscope's frequency measurement is 89.375kHz in this case, and this represents the frequency measured across 10 cycles. Fres is therefore 10 times this value, which is 893.75kHz

3.6 Q-Factor Measurement with an Oscilloscope

According to Equation 4, Q-factor can be measured by identifying how many resonator cycles N it takes for the waveform's envelope to decay by a factor of 0.37. Figure 12 illustrates this measurement. It is based on the same oscilloscope settings as Figure 11, except the time base has been extended for greater resolution and new cursors have been added.

The left hand cursor a has been positioned at the first peak of the COSA waveform that is at least half a cycle away from the final edge on DR1, as before. The peak EMF at this point is measured with the upper horizontal cursor: 624mV. 0.37 times this value is 231mV. The lower horizontal cursor has been set to this value (or as close as possible give its limited resolution: 228mV). The right hand vertical cursor b has been adjusted to the approximate location where the resonator decay envelope intersects the lower horizontal cursor, marked with a circle below. Note that this point does not coincide with a peak of the waveform because the target value of 231mV lies approximately half way between the adjacent positive peaks.

The number of resonator cycles between the left hand vertical cursor a and the right hand vertical cursor b is 5.5. According to Equation 4, the resonator's Q-Factor is therefore 17.3.

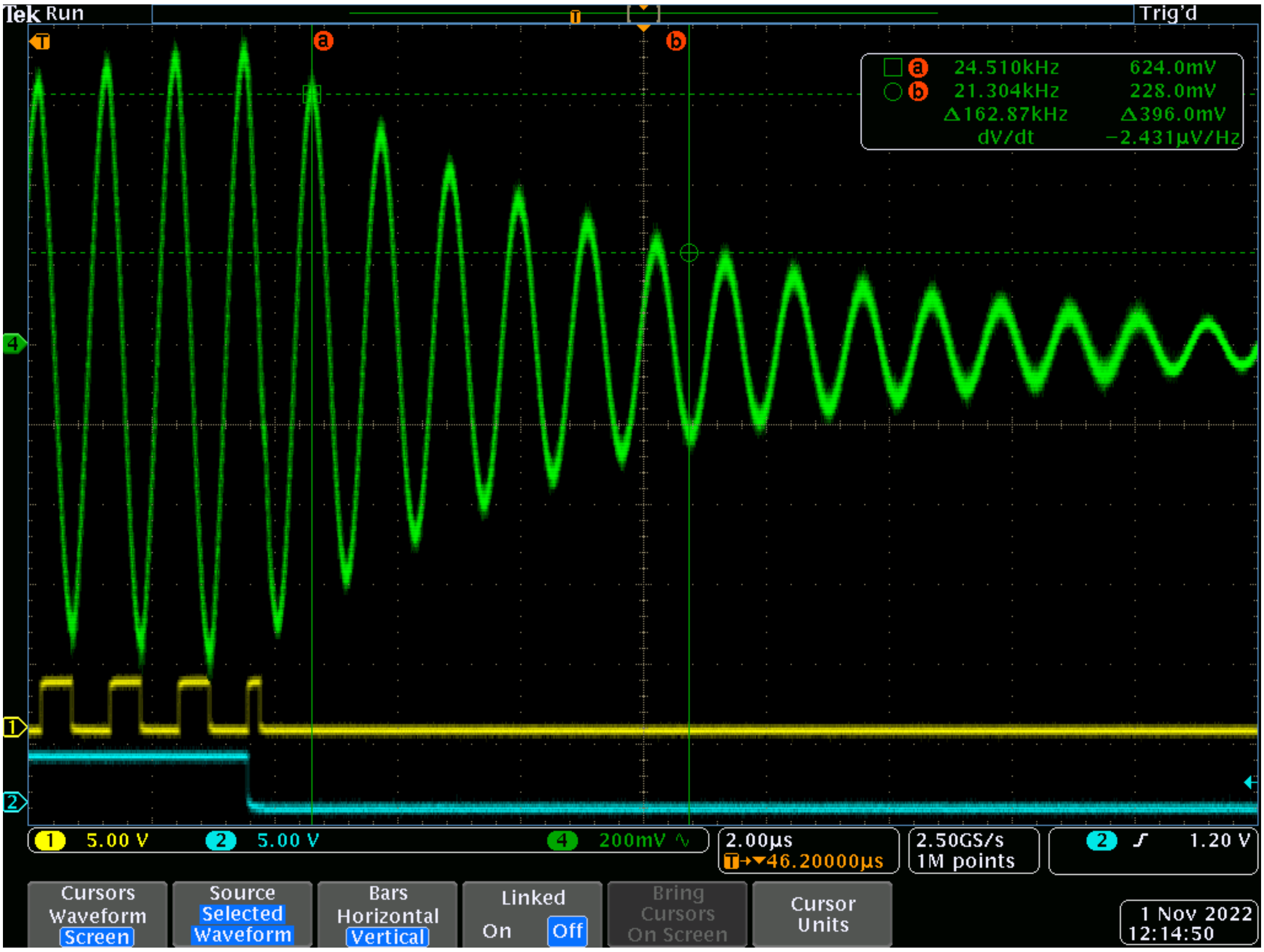

Figure 12 Resonator Q-Factor measurement

3.7 Measurements Using an Encoder IC

When connected to Resonant Inductive Encoder IC circuitry as in Figure 1, the IC can report diagnostic data over its debug interface. This includes resonator frequency and amplitude measurements.

The reported resonator frequency is a useful guide for design purposes. Encoder ICs use an on-chip frequency reference with an accuracy ~ ±2%. Resonator frequency measurements are therefore subject to the same tolerance. When the absolute frequency value is required to higher accuracy, measurement with an oscilloscope as in section 3.5 is preferred.

There are many situations when it is sufficient to measure only changes in resonator frequency, for example when determining the effect of nearby metal. In this case the Encoder IC’s frequency measurement can be used, because the measurement of interest is usually the change in frequency between free space and with metal nearby, and not the absolute value of frequency.

Encoder ICs do not measure Q-factor, and when accurate measurements of Q-factor are required it is preferred to use the approach detailed in section 3.6. They do however report Amplitude, and this measurement can often be used instead of Q-factor measurement. For example, nearby metal can cause a reduction in both Q-factor and coupling, but it is often sufficient to measure the reduction in Amplitude whose value depends on both of them.

4 Metal Integration and Screening

4.1 Importance of Amplitude and Q-Factor

The Resonant Inductive Encoder IC measures signal Amplitude and its measured value is available to a host for diagnostic purposes. Amplitude is important because high values tend to yield better performance, in particular resolution. Please see section 2.4. In an interference free environment the approximate relationship between Amplitude and resolution is expressed in Equation 15. Note that doubling Amplitude increases Expected Noise Free Resolution by 1 bit.

Metals near the sensor and target tend to reduce both Amplitude and Q-Factor. Care must therefore be taken to ensure that any performance degradation due to nearby metal is acceptable in the customer's application.

It is recommended to avoid metal environments that reduce Amplitude to a factor of 0.5 or less of its free space value. Reducing Amplitude by a factor of 0.5 will reduce noise free resolution by about 1 bit. Even if this can be tolerated in the application, such a large reduction in Amplitude is a sign of stress. In these cases please contact CambridgeIC for recommendations.

The Resonant Inductive Encoder IC requires a minimum Amplitude to function correctly. It also requires a minimum Q-factor, as noted in section 3.3. If these limits are not respected there is a chance of invalid measurements. Care must therefore be taken to respect the published limits, especially when operating with a big gap between sensor and target and in environments when metal has a substantial effect.

4.2 Importance of Resonator Frequency

The frequency of the target's resonator can change significantly when operated near metal.

It is recommended to avoid metal environments that increase or decrease resonator frequency by 10% or more relative to its free space value (equivalent to a decrease or increase in LRES of 20%).

Smaller changes in resonator frequency can be corrected by appropriate choice of resonator capacitance CRES (section 5), to ensure the resonator frequency remains centered on the Resonant Inductive Encoder IC's tuning range in use. If resonator frequency changes by more than 10% relative to free space when integrated with a product's metal environment, please contact CambridgeIC for recommendations.

If the target can move relative to metal parts, for example due to changes in gap to the metal due to tolerances and mechanical movement inside the product, then this will contribute to variability in the resonant frequency. This variability must be kept within an acceptable range, see section 5.5.

4.3 Definition of Free Space

References to "free space" below and in sensor datasheets mean that the sensor and target are far away from metals and magnetic materials.

Plastics and other non-conductors do not influence the sensor and target at all, even when completely surrounding them, and this also counts as "free space" for current purposes.

Some materials are apparently quite conductive, for example sea water and carbon fibre. However their resistivity is many orders of magnitude greater than that of metals, and they do not influence the sensor and target significantly.

4.4 Metal Proximity Definitions

This section defines basic arrangements of metal near the sensor and target that are referenced later in this document and in sensor datasheets. As noted in sections 4.5 and 4.6 the effects of different metals can be significant. Results presented in a sensor's datasheet for aluminium are not representative of steel, and vice versa.

Figure 13 illustrates a metal plate behind the target. In this case the main dimension influencing the effect of the metal is the distance of the metal plate behind the target. The metal plate diameter does not affect measurements significantly providing it is greater than the target's diameter plus twice the distance of the metal plate behind the target. Unless otherwise stated, this applies to measurements based on this arrangement.

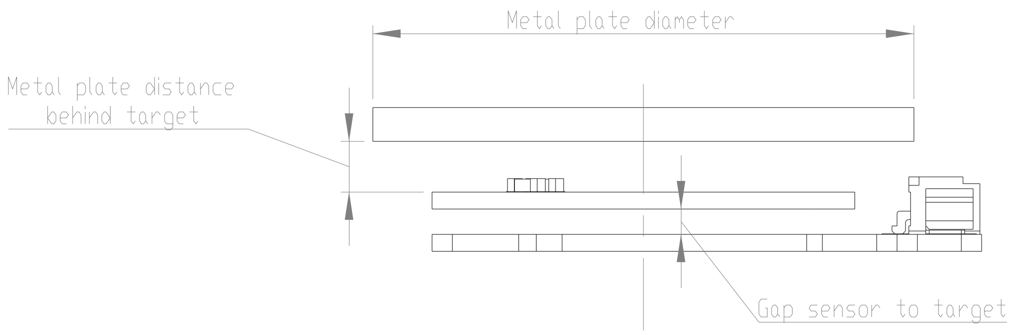

Figure 13 Metal plate behind target

Figure 14 is similar, except this time the metal plate is behind the sensor. The metal plate diameter does not affect measurements significantly providing it is greater than the sensor's diameter plus twice the distance of the metal plate behind the sensor. Unless otherwise stated, this applies to measurements based on this arrangement.

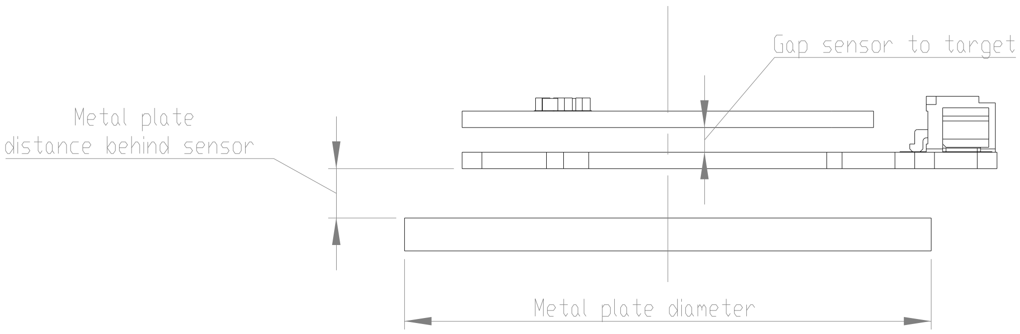

Figure 14 Metal plate behind sensor

Holes in metal plates positioned along the rotation axis do not normally affect measurement results significantly, providing their diameter is similar or less than that of the centre hole in the sensor or target.

Figure 15 illustrates a metal shaft through the sensor and target. This is an important arrangement because the target is designed to allow mounting to a metal shaft, and rotary sensors and targets usually have large central holes for a shaft. In this case the main dimension of importance is the shaft diameter.

Measurements taken with a shaft through the sensor and target are usually done with a shaft that extends axially at least 10mm beyond the sensor and target. This makes the measurements representative of longer shafts too. Shorter shafts will have slightly smaller effects.

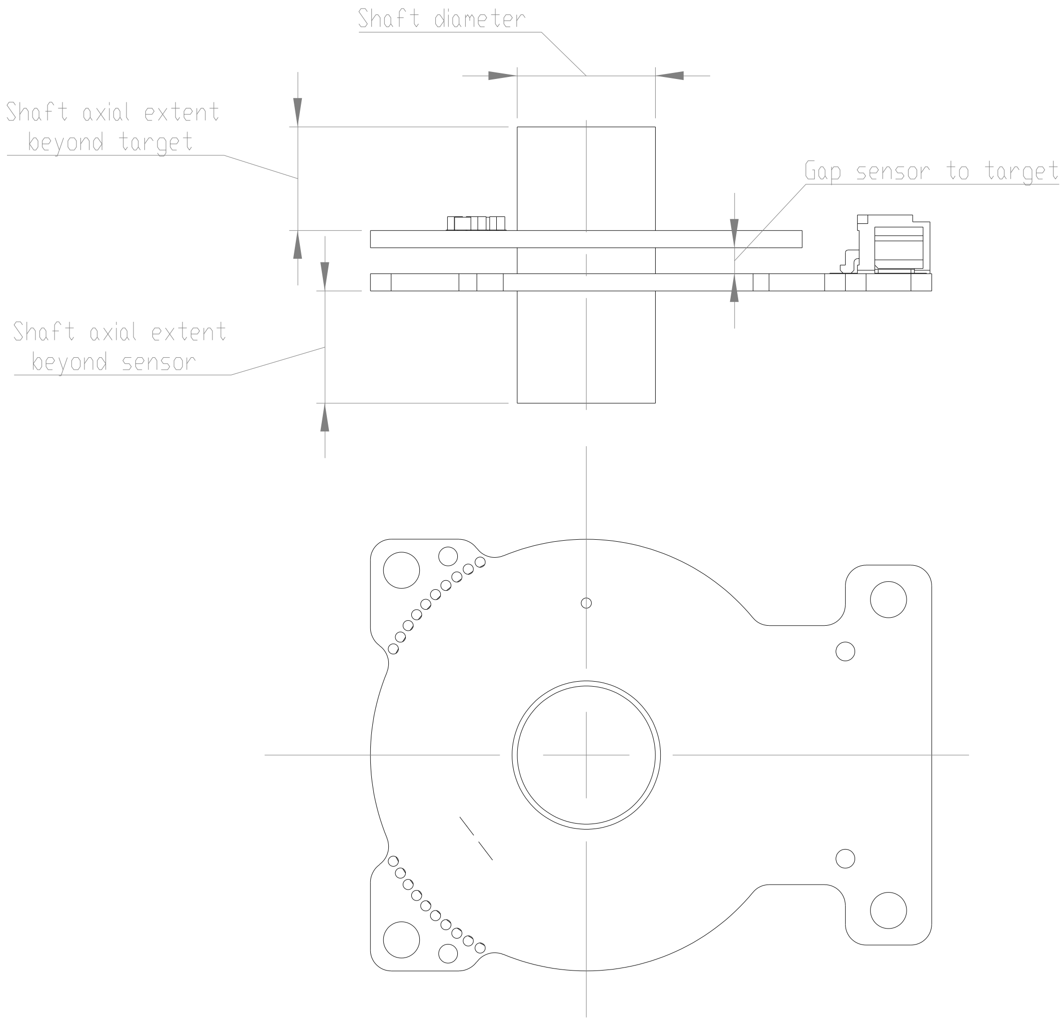

Figure 15 Metal shaft through sensor and target

This arrangement is also representative of hollow shafts, in which case only the outside diameter matters.

Figure 16 illustrates metal surrounding the sensor and target. This arrangement simulates the parts mounted inside a circular housing, or in a round hole in a metal part. In this case the main dimension of importance is the surround inside diameter.

Measurements taken with a metal surround are usually done with a surrond that extends axially at least 10mm beyond the sensor and target. This makes the measurements representative of longer surrounds too. Shorter surrounds will have slightly smaller effects.

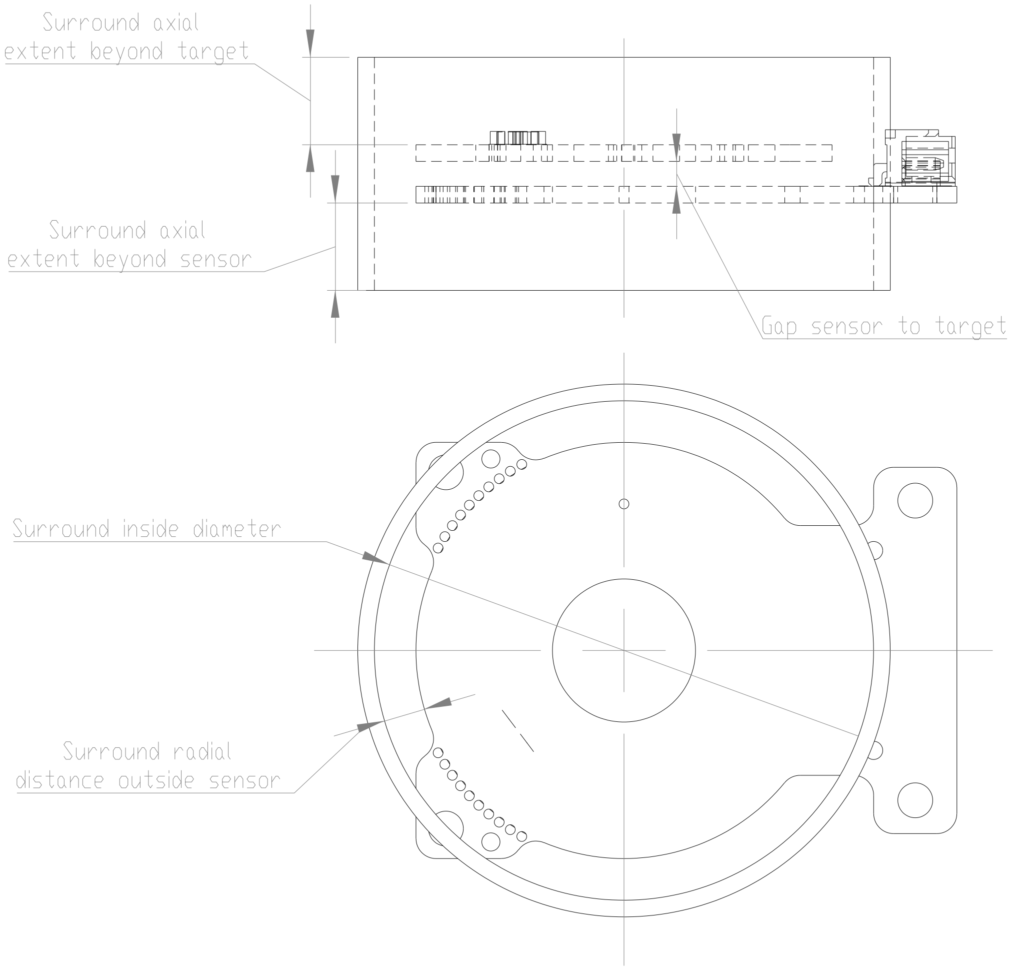

Figure 16 Metal surrounding sensor and target

The sensor coils may be implemented on a PCB that is shared with electronic components. In this case the electronics will usually require a ground plane that may surround the sensor coils. Figure 17 illustrates a ground plane surrounding the sensor coil area. In this case the ground plane is continuous – it forms a continuous conductive lop around the sensor coil area (a "shorted turn"). The inside diameter of the copper opening in the ground plane is denoted Copper Ground Plane Opening Diameter.

When the Copper Ground Plane Opening Diameter is small, so that there is only a small break between the ground plane and sensor area, the effect of the ground plane on detected Amplitude and frequency is greater.

Where possible, the ground plane should be cut as illustrated in Figure 18. This significantly reduces the effect of the ground plane, because it prevents currents from flowing around it, removing the "shorted turn" around the sensor and target.

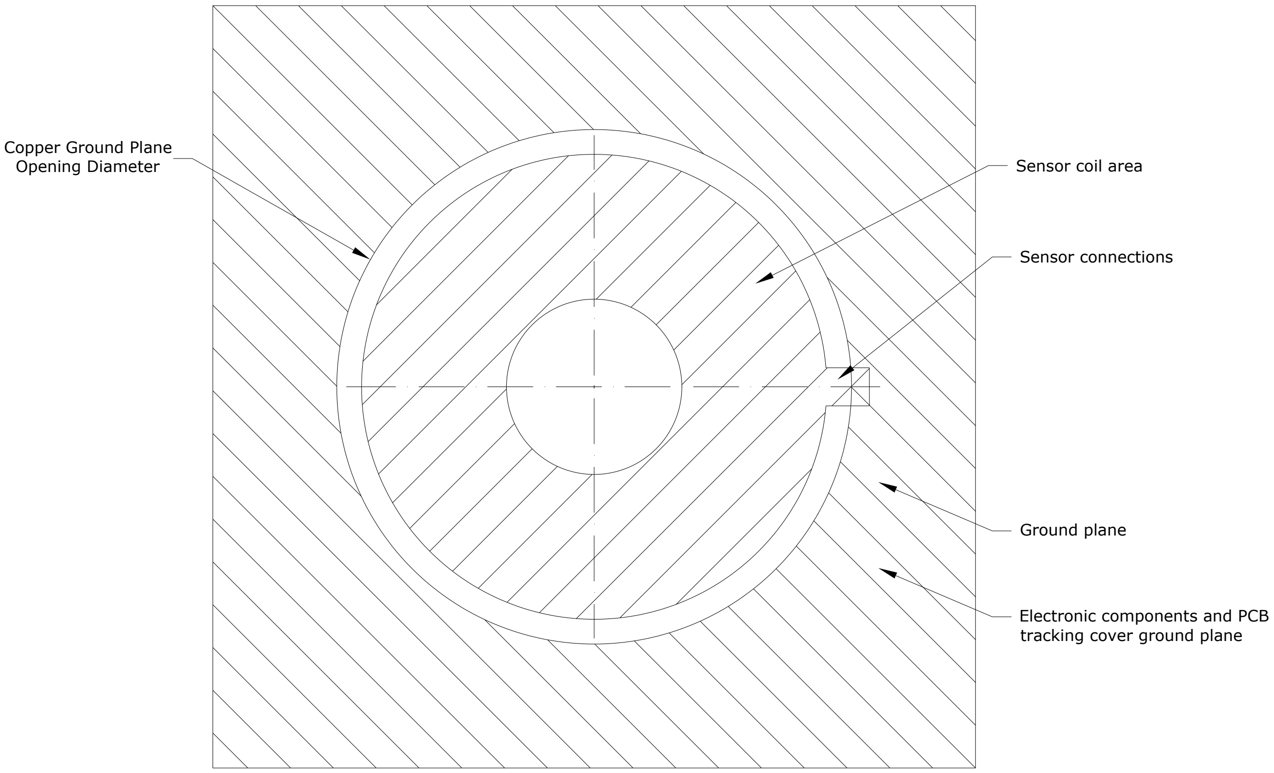

Figure 17 Continuous ground plane around sensor

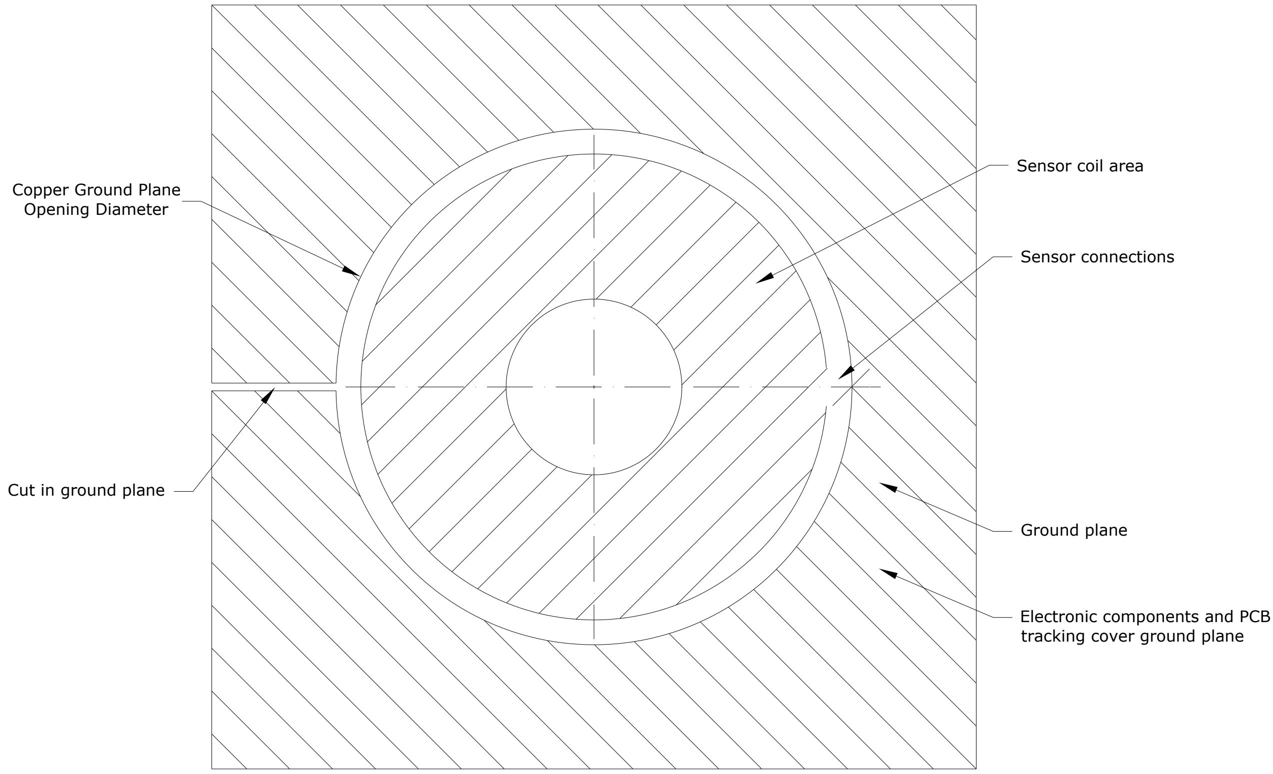

Figure 18 Cut ground plane around sensor

Sensor datasheets usually present data for each metal arrangement above individually. Where a customer's product environment includes two or more of these metal arrangements, the combined effect can be estimated as the combination of the individual effects. For example, if aluminium 3mm behind the sensor reduces Amplitude by 16%, to a factor of 0.84, and a central 8mm shaft reduces Amplitude by 11%, a factor of 0.89, then their combined effects will be to reduce Amplitude by a factor of about 0.84 x 0.89 = 0.75 (all relative to free space). Similarly, if the same aluminium behind the sensor increases resonator frequency by 2% and the same steel shaft reduces it by 0.2%, then the combined effect will be to increase frequency by about 2% - 0.2% = 1.8%.

4.5 Effects of Nearby Aluminium

Aluminium tends to repel AC magnetic fields. The fields set up eddy currents on the adjacent surface of the aluminium that prevent them from penetrating the material. Most grades of aluminium and its alloys have similar resistivity, so it does not usually matter what material grade or alloy are used.

Figure 19 illustrates the magnetic field generated by a current-carrying trace on the resonator PCB. In Figure 19(a) there is no nearby metal, and in Figure 19(b) there is nearby aluminium. The aluminium in Figure 19(b) squeezes the field lines away.

The coupling between the resonator trace and a trace on the sensor PCB is related to how many of the magnetic field lines surround the sensor trace. In the free space case of Figure 19(a) there are 2 field lines surrounding the sensor trace. However the presence of aluminium in Figure 19(b) shifts the field lines so that only one now surrounds the sensor trace. The aluminium reduces the coupling between the resonator trace and sensor trace. The same principle applies to a complete resonator coil and sensor coil, each comprising many traces. Aluminium near the sensor and/or resonator tends to reduce coupling, and this in turn means lower signal Amplitude. A lower Amplitude means worse performance, in particular worse resolution.

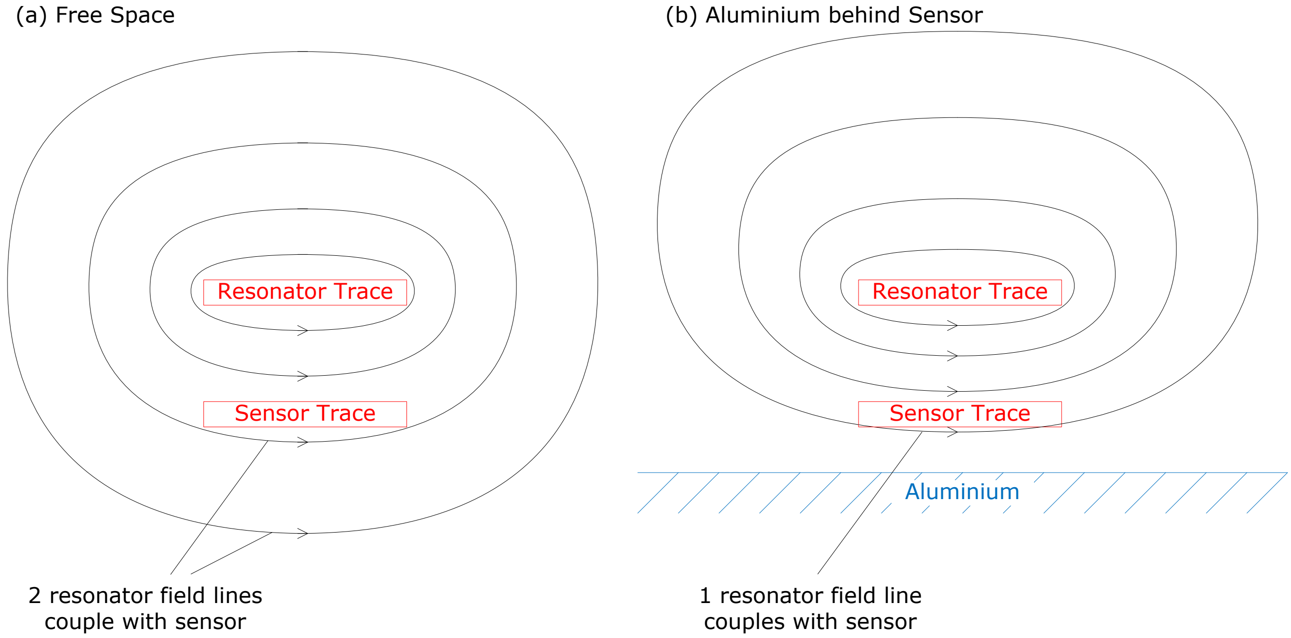

Figure 19 Reduction in coupling with nearby aluminium

The Radial Extent of a rotary sensor is defined in Figure 20. The reduction in Amplitude due to nearby aluminium is usually insignificant when the distance between that aluminium and a sensor or target is greater than half the Radial Extent. Typical precision through hole rotary sensors have a Radial Extent of about 10mm, so the effect of aluminium on Amplitude is insignificant with a separation greater than 5mm.

Figure 20 Definition of Radial Extent

Smaller pieces of aluminium near to the sensor or target tend to have less effect on Amplitude and hence resolution. For example the small aluminium disc illustrated in Figure 22 will have less effect than the larger ring shown in Figure 21.

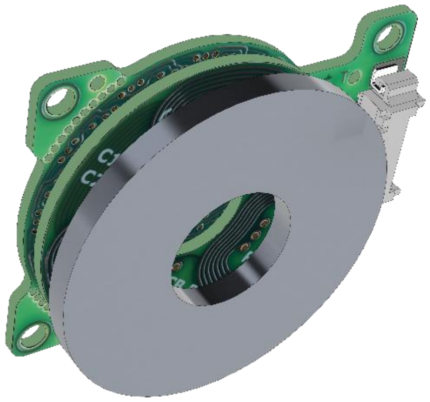

Figure 21 Uniform aluminium behind sensor

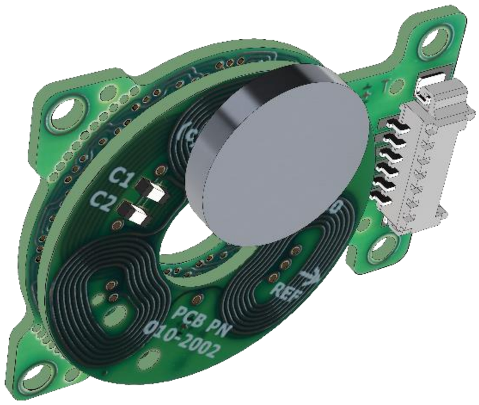

Figure 22 Nonuniform aluminium behind sensor

However these two arrangements of aluminium will affect accuracy differently. The aluminium ring of Figure 21 has rotational symmetry about the rotation axis. This symmetry helps to minimise its effect on accuracy. However the smaller disc of Figure 22 will affect accuracy more. Eddy currents flowing around the disc's face adjacent the sensor, induced by the resonator, will disturb sensor measurements in a non-uniform way.

Holes in the uniform aluminium ring of Figure 21 with diameter less than about 4mm will not significantly affect accuracy, because eddy currents will tend to flow around holes without significant disturbance. The aluminium surrounding such holes will also tend to screen the effects of any steel screws in those holes, especially if countersunk and flush with the aluminium surface adjacent to the sensor or target.

Small pieces of aluminium have a smaller effect on both Amplitude and accuracy. For example, an aluminium disc with 5mm diameter positioned as in Figure 22 with a gap of 2mm to the sensor will affect accuracy by less than about ±0.05°.

When there is aluminium closer to target than the its Radial Extent, it is likely there will be a significant change in the target's resonant frequency relative to Free Space. In this case it is recommended to follow the procedures of Section 5, to ensure the nominal resonator frequency is sufficiently close to the centre of the Resonant Inductive Encoder IC's tuning range.

4.6 Effects of Nearby Steel

Steel is much less conductive than aluminium, which means that eddy currents penetrate to a greater depth. This means that steel tends to repel AC magnetic fields less than aluminium, causing a smaller change in resonator frequency. On the other hand, steel tends to cause a much greater reduction in the Q-factor of the resonator, because more energy is lost when AC fields from the resonator penetrate the steel and cause lossy eddy current flow.

For a given shape and proximity of nearby metal object, steel will therefore have a much greater adverse effect on Amplitude than aluminium. The grade of steel, including whether or not it is austenitic, tends not to have a significant effect.

Steel and stainless steel screws have a smaller effect than larger pieces of steel. Such screws usually have little effect on Amplitude and accuracy providing they are to the side of the sensor and target and the screw heads are not directly behind them.

If the effect of steel on Amplitude is found to be excessive and its presence is unavoidable, there may be an option to shield the sensor and target against its influence by adding an aluminium screen between the steel and the sensor/target. Note that the shield should be thick enough to repel AC fields at the operating frequency, see section 4.7.

4.7 Effect of Material Thickness

AC magnetic fields at the Type B sensor operating frequency of around 833kHz do penetrate aluminium slightly – roughly up to the skin depth at this frequency: 90µm. The thickness of the aluminium does not matter much providing it is greater than about half this figure, 45µm.

However if the aluminium is thin, for example aluminium foil (typically 15µm), AC magnetic fields will penetrate the material. Since these eddy currents penetrate the material, they tend to couple more with the field than thicker aluminium. This causes much greater losses and reductions in Q-factor and Amplitude. Thin aluminium including foil therefore tends to behave more like steel, and should be avoided.

Copper is more conductive than aluminium, and skin depth at the operating frequency is approximately 70µm. Copper with half this thickness or greater, 35µm, behaves like nearby aluminium, as described in section 4.5 Note that copper PCB foils are commonly 35µm thick ("1oz per square foot"), so this includes PCBs with a solid ground plane.

4.8 Through Hole Sensors with Metal Shafts Inside

When designing targets for through shaft operation, special steps are taken to minimise the fields they generate that pass through their centre holes. This is to allow a customer to mount the target to a rotating metal shaft, with that shaft also passing through the sensor.

An aluminium shaft tends to have less effect on Amplitude than a steel shaft. Nevertheless, steel shafts can be used and the steel has a relatively small effect. Please refer to the sensor's datasheet for examples.

4.9 Use of Target Flexible Ferrite Screen

Aluminium closer than about 3mm behind the target can significantly reduce Amplitude and hence performance. In this case it may be preferable to laminate flexible ferrite screening material to the rear of the target, to screen it against the influence of the aluminium. If absolutely necessary, the gap between the ferrite screening material and aluminium can be reduced to zero, as illustrated in Figure 23.

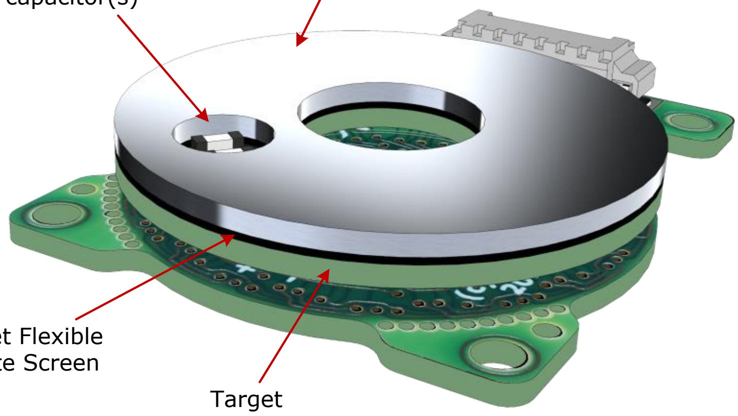

Figure 23 Target shielding

Possible ferrite screening materials include Wurth "WE-FAS EMI Flexible Absorber Sheet" material, order code 34403. This is 0.33mm thick including adhesive on one side, and has a magnetic permeability of 100 at 1MHz. Customers must assess suitability of any such material themselves, including its mechanical stability at the rotation speeds and temperature range required.

The screening arrangement of Figure 23 can also be used to reduce the amount of AC magnetic field interference coupled into the target's resonator coil. The aluminium screen acts to repel the AC magnetic field, and must be close to the target for best effect. The flexible ferrite screen prevents excessive Amplitude reduction caused by the close proximity of the aluminium screen.

Magnetic screening material near the target significantly increases the resonator coil's inductance. It is essential to follow the procedures of section 5 to ensure an appropriate tuning capacitance CRES is used for such a design. It is also essential to allow for variation in resonator frequency caused by the material, for example due to variability in the material's permeability and variability in the distance between the screening material and any aluminium behind the sensor.

4.10 Importance of Measurement

Customers are strongly encouraged to take measurements with actual hardware, in order to understand the effects of different metal environments for the sensor and target. The most useful and basic test to perform is to measure Amplitude and reported frequency (section 3.7), with the target and sensor in free space and then mounted inside the customer's metal environment or an experimental mock-up of it, with the same gap between sensor and target and ideally at the same angular position. A comparison can then be made between the two arrangements, to establish the effect of the nearby metal on Amplitude and resonator frequency.

Actual measurements are essential when evaluating the effect of screening materials. In particular, care must be taken that the material does not cause excessive variability in resonator frequency (section 5.5). This situation may be encountered where the target is screened as in Figure 23 and there is also aluminium behind the sensor as in Figure 21. In this case the resonator frequency will change substantially with the gap to the aluminium. The system's budget for resonator variability must take this frequency variability into account, which means taking measurements at maximum and minimum gap between screening and aluminium.

5 Target Resonator Frequency Tuning

CambridgeIC's Resonant Inductive Encoder ICs detect the frequency Fres of the target's resonator, and they adjust their excitation and detection frequency to match. This makes them highly tolerant of frequency variability.

The selected Resonant Inductive Encoder IC's datasheet includes a specification for its centre frequency and tuning range. It is essential to ensure that the resonant frequency of targets it is used with always falls within the tuning range, otherwise measurements may become invalid.

It is preferable to operate within the centre half of the tuning range for best resolution, because detected Amplitude decreases slightly when the difference between the resonator's frequency and the IC's centre frequency is outside that range.

5.1 Identifying Nominal LRES

If the sensor and target are mounted in free space and the target PCB is built according to the tolerances specified by CambridgeIC, then the resonator coil's inductance LRES should equal the value provided in the sensor's datasheet. Otherwise, it is necessary to measure the value of LRES for representative target PCBs and in the final product's metal environment.

Ideally a target PCB representative of a customer's production process should be used for measurement in the final product's metal environment. This can be obtained by measuring the free space value of LRES for a representative population of target PCBs, and selecting a part with a central value.

Inductance measurements should ideally be taken with an LCR bridge whose test frequency is adjustable. The ideal test frequency is 1MHz, although measurements can also be taken at 100kHz if that is not possible. Measurements taken at a test frequency of less than 100kHz should be treated with caution, because the relatively low impedance of the resonator coil at these frequencies may cause significant errors.

Where possible, the LCR bridge should be configured to report series inductance and resistance values, rather than parallel ones.

Having identified a target with central resonator coil inductance LRES value in free space, this target's LRES value should now be measured in the final product's metal environment, including any screening if present.

There may be sources of variability in this measurement, for example due to the relative positions of target and metal parts. If the gap between the target and any metal can vary significantly then this will introduce variability to the value of LRES. In this case it is recommended to identify maximum and minimum values for LRES, and to use a central value for calculating resonating capacitance CRES.

5.2 Calculation of CRES

The ideal resonating capacitance value CRES can now be calculated by rearranging Equation 5 to Equation 9.

Equation 9

$$CRES = \frac{1}{(2\pi \times Fres)^2 \times LRES}$$

The central value of LRES established in section 5.1 should be used for LRES. The nominal centre frequency of the Resonant Inductive Encoder IC should be used for Fres.

5.3 Allowance for Self-Capacitance

Targets comprise printed coils on a PCB, and they are implemented on multiple PCB layers in close proximity. They therefore have self-capacitance distributed across coil conductors. This can be lumped into an effective self-capacitance denoted CSELF. Where significant, an approximate value is specified in the sensor's datasheet. To establish the total additional resonator capacitance required in the form of discrete capacitors, subtract this CSELF value from CRES as in Equation 10.

Equation 10

$$CCAPS = CRES - CSELF$$

5.4 Selection of Preferred Capacitors for CCAPS

Target PCBs usually include a footprint for two 0603 SMD capacitors C1 and C2. Having obtained the required value for CCAPS, the next step is to identify preferred capacitor values for C1 and C2 that add up to CCAPS. It is usually possible to select preferred values of C1 and C2 such that their sum is within 1.7% of a target value CCAPS, when selecting from E12 capacitor values.

It is strongly recommended to use capacitors with COG/NPO dielectric for C1 and C2. A ±5% tolerance is usually acceptable, although tighter tolerance may be required in some situations (section 5.5).

The sensor's datasheet includes details of assembled targets available form CambridgeIC for evaluation purposes. This includes the voltage rating used for C1 and C2. It is essential to use the same voltage rating or greater.

5.5 Verifying Resonant Frequency and its Variability

Having established candidate values for C1 and C2, it is now recommended to check the expected range of the resonator frequency Fres across systems and temperature. Table 1 lists sources of variability that might typically be encountered.

Table 1 Sources of variability in CES and LRES

Source	Typical contribution to CRES or LRES tolerance	Comments
C1 + C2 manufacturing tolerance	±5%	Use tolerance of actual parts selected.
C1 + C2 tolerance across operating temperature	0.2%	Based on ±80° temperature change and ±25ppm/°C temperature coefficient. Use actual manufacturer data and temperature range.
LRES manufacturing tolerance	±2%	Simulated, based on finished thickness tolerance of ±10%. Use actual manufacturing variability if known and/or critical.
LRES tolerance across operating temperature	±0.1%	Based on ±80° temperature range and 11ppm/°C thermal expansion of FR4 PCB material. Usually insignificant.
Variable gap metal to target if present	Application specific	Measure in final product environment.
Flexible ferrite screening material if present	Material and application specific	Difficult to quantify – need to test and monitor variability across production.
Variable gap aluminium to ferrite screening if present	Application specific	Measure in final product environment.

In the absence of metal and screening materials, the sum of variability in CRES and LRES is ±8%, based on the values given in Table 1. This yields variability in Fres of ±4%, according to Equation 6.

Once actual values and tolerances are known, extreme values can be added together to yield minimum and maximum values for CRES and LRES. The minimum values should be substituted into Equation 5 to yield the maximum expected value of Fres. The maximum values should be substituted into Equation 5 to yield the minimum expected value of Fres.

The resulting expected range of Fres values should then be compared to the Resonant Inductive Encoder IC's tuning range given in its datasheet. The Fres range is OK if it falls within this range, ideally within the central half of the range for best resolution.

Please contact CambridgeIC for advice if it appears impossible to achieve the necessary tolerances.

5.6 Verifying Q-Factor

For most purposes the Amplitude value reported by the Resonant Inductive Encoder IC is a good guide to system health. However it is possible to obtain high Amplitude values when Q-factor is below the minimum specified in the Resonant Inductive Encoder IC's datasheet, for example because a small gap is maintained between the sensor and target. It is recommended to verify that the Q-factor of the resonator remains acceptable, by measuring parts in the final product metal environment using the approach detailed in 3.6. This is particularly important when there is steel near the target (except through its centre hole).

6 Coordinate System

Measurement results in sensor datasheets are based on the coordinate system illustrated in Figure 24.

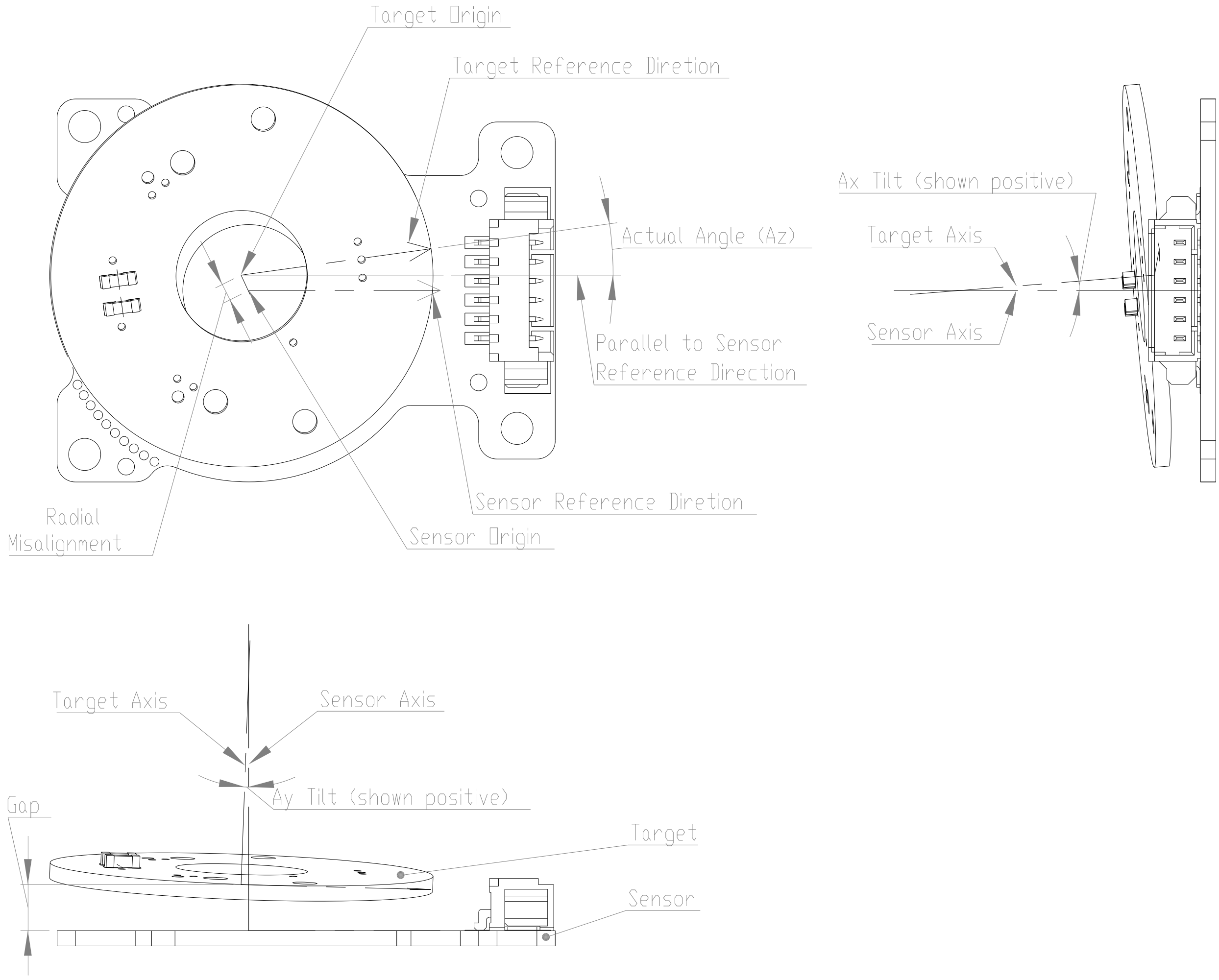

Figure 24 Parameters defining alignment of target relative to sensor

The Target Reference Direction, Target Axis, Sensor Reference Direction and Sensor Axis are defined in the sensor's datasheet. The sensor's positive x-axis is along the Sensor Reference Direction. The sensor's positive z-axis is along the Sensor Axis, in the direction of the target. The sensor's positive y-axis is perpendicular to both, pointing upward as drawn in the top left view of Figure 24.

The primary purpose of the system is to measure the angle of the target relative to the sensor. The Resonant Inductive Encoder IC reports its best estimate of the Actual Angle, which is defined as the angle between the Target Reference Direction and the Sensor Reference Direction, projected onto the plane of the sensor PCB.

The target is usually mounted to a rotating shaft. Due to mechanical mounting tolerances the Target Origin may not exactly coincide with the rotation axis, and the Target Axis may not exactly run along the rotation axis. Similarly, the Sensor Origin may not exactly coincide with the rotation axis and the Sensor Axis may not exactly point along the rotation axis.

Radial Misalignment is the distance between the Sensor Origin and the Target Origin projected onto the plane of the sensor PCB. In a typical application it will vary with Actual Angle because the Target Origin does not exactly coincide with the rotation axis.

Ax and Ay tilt are measures of target tilt angles relative to the sensor, about its x-axis and y-axis respectively. In a typical application they will vary with Actual Angle because the Target Axis is not exactly parallel to the rotation axis. The term Angular Misalignment used in sensor datasheets refers to either Az or Ay tilt, whichever causes the greatest error.

Gap between sensor and target is defined as the distance of the Target Origin above the plane of the sensor.

7 Performance Definitions

7.1 Transfer Function

The Resonant Inductive Encoder IC can be configured to output position readings over different interfaces, and the interpretation of the result depends on the interface and how it is configured. For example its SPI interface can output position as a 32-bit signed integer over its debug interface, here denoted *PosOutI32*. When processing an absolute rotary sensor, the full I32 range represents 360° of rotation. Reported angle in degrees may therefore be calculated by Equation 11.

Equation 11

$$Reported\ Angle\ in\ Degrees = \ (PosOutI32/2^{32}) \times 360°$$

This yields an angle result in the range -180°≤angle<+180°. Alternatively, if *PosOutI32* is instead interpreted as an unsigned integer, the result will be in the range 0°≤angle<360°.

This figure is nominally equal to the Actual Angle defined in section 6. The figures differ due to random noise, Linearity Error and Offset Error, as expressed in Equation 12.

Equation 12

$$Reported\ Angle - ActualAngle = RandomNoise + LinearityError + OffsetError$$

7.2 Random Noise and Resolution

Random noise is inherent in any analog measurement. The random noise present in the IC's reported measurements can be considered Gaussian (*well behaved noise*). There are two general measures of Random Noise, Peak to Peak Noise and Standard Deviation. Defining Peak to Peak Noise such that it encompasses 99.9% of samples (100% is physically impossible due to the statistical nature of noise) yields the relationship of Equation 13.

Equation 13

$$Peak\ to\ Peak\ Noise = 6.6\ \times Standard\ Deviation$$

Another common measure of noise used in encoders is Noise Free Resolution. Noise Free Resolution may be calculated from Peak to Peak Noise using Equation 14.

Equation 14

$$Noise\ Free\ Resolution = \ \log_2 \frac{360°}{Peak\ to\ Peak\ Noise\ in\ °}$$

Resonant Inductive Encoder ICs include on-chip adaptive position filtering that can be used to trade resolution and responsiveness. The filter can also be configured to compensate for a small on-chip processing delay. Resolution measurements presented in sensor datasheets are of raw unfiltered position data with delay compensation disabled, unless otherwise noted.

Datasheet measurements of Linearity Error and Offset Error are separated from the effects of random noise by averaging a sufficiently large number of reported angle measurements.

7.3 Expected Resolution

As explained in section 2.4 the noise inherent in the system's reported position output is a function of Amplitude. In an interference free environment that noise is largely generated inside the Resonant Inductive Encoder IC itself. The noise free resolution of the Resonant Inductive Encoder IC's position output therefore depends approximately on signal Amplitude. The relationship can be approximated by Equation 15.

Equation 15

$$Expected\ Noise\ Free\ Resolution = \log_2 \left[\frac{Amplitude\ \times Subtype}{3}\right]$$

Measurements of actual position noise tend to vary, in particular with Actual Angle. Expected Noise Free Resolution is a more stable measure because Amplitude measurements are stable. Equation 15 is conservative, and tends to yield the worst resolution across Actual Angle. It is therefore the usual measure quoted in Type B sensor datasheets.

7.4 Linearity Error and Offset Error

Linearity Error is the deviation of the transfer function from a straight line. In this case the slope of the straight line is fixed at 360° per 360° because of the continuous rotary nature of the sensor. Measurements taken at 0° and 360° are identical. So Linearity Error simply measures deviations relative to an Offset Error.

There are two main contributions to Offset Error: one from the sensor and one from the target. Their origin is the accuracy with which the angle of PCB copper coil patterns on each layer can be aligned with registration features, typically drilled holes.

7.5 Differential Non-Linearity

Differential non-linearity (DNL) is a measure of the sensor's instantaneous velocity accuracy. The Resonant Inductive Encoder IC includes interfaces that include a velocity measurement. Alternatively the host can take position readings and process them to estimate velocity. Either way, the accuracy of velocity data depends on the accuracy of the sensor.

When the target is rotating at constant angular velocity v, the system's reported angle is given by Equation 16.

Equation 16

$$Reported\ Angle\ = v \times t + LinearityError(x) + Offset\ Error$$

t is time and x is Actual Position. Linearity Error is a function of x, so here it is written LinearityError(x). Equation 16 ignores the effect of random noise. Random noise is important for velocity measurement, but its effect can be determined separately to the effects of DNL and so it is not included in the equation above.

Velocity is the differential of position with respect to time. Differentiating Equation 16 yields Equation 17.

Equation 17

$$Reported\ Velocity\ = v + \frac{d}{dt} LinearityError(x)$$

The differential of LinearityError(x) with respect to time can be rewritten using the chain rule to yield Equation 18.

Equation 18

$$\frac{d}{dt} LinearityError(x) = \frac{d}{dx} LinearityError(x) \times \frac{dx}{dt}$$

The differential of x with respect to time is simply velocity v, so Equation 18 may be rewritten as in Equation 19

Equation 19

$$\frac{d}{dt} LinearityError(x) = \frac{d}{dx} LinearityError(x)\ \times v$$

This allows Equation 17 to be rewritten as shown in Equation 20

Equation 20

$$Reported\ Velocity\ = v\ \times \left[1 + \frac{d}{dx} LinearityError(x)\right]$$

Velocity error is Reported Velocity minus actual velocity v, as expressed in Equation 21.

Equation 21

$$Velocity\ Error\ = Reported\ Velocity - v$$

Substituting for Reported Velocity from Equation 20 yields Equation 22.

Equation 22

$$Velocity\ Error\ =\ v\ \times \left[\frac{d}{dx} LinearityError(x)\right]$$

Fractional Velocity Error is the ratio of Velocity Error to actual velocity v, as expressed in Equation 23.

Equation 23

$$\frac{Velocity\ Error}{v} = \frac{d}{dx} LinearityError(x) = DNL$$

Fractional Velocity Error is therefore equal to the rate of change of Linearity Error with x (Actual Position). That is, it is equal to the slope of the Linearity Error function, also referred to as Differential Non-Linearity (DNL).

Type B sensor datasheets include DNL measurements, to help customers establish the impact of sensor errors on their system's performance.

Datasheet measurements are based on measurements of reported position at a large number of points around a circle. In this case the differential is calculated using discrete steps of Actual Angle Δx, as in Equation 24.

Equation 24

$$DNL = \frac{LinearityError(x + \Delta x) - LinearityError(x)}{\Delta x}$$

Note that Resonant Inductive Encoder ICs can be configured to filter position and velocity measurements. This tends to reduce errors in reported velocity (and velocity calculated from reported position), especially at high velocity. Measurements presented in sensor datasheets are based on raw, unfiltered data.

Note also that the DNL figure is not a lower bound on achievable velocity accuracy. There are tactics for achieving much better velocity accuracy if required. For example measuring the time it takes for the shaft to rotate one turn back to the same angular position. This does not suffer from any error due to sensor non-linearity because the error at the selected position is the same from one turn to the next.

7.6 Sensitivity to Radial Misalignment

Sensitivity to Radial Misalignment is measured by comparing Reported Position values with and without Radial Misalignment, and expressing the result in "angle per distance" units using Equation 25.

$$Measured\ Sensitivity\ to\ Radial\ Misalignment = \frac{Reported\ Position(with\ Radial\ Misalignment) - Reported\ Position\ (no\ Radial\ Misalignment)}{Radial\ Misalignment}$$

Equation 25

This depends on Actual Angle, Angular Misalignment, Gap and so on, so typically a worst case value is presented.

When applied to an optical or magnetic encoder without the benefit of a balanced design, the worst case sensitivity is given by Equation 26.

Equation 26

$$Imbalanced\ Sensitivity\ to\ Radial\ Misalignment = \frac{180°}{\pi} \times \frac{1}{Code\ Radius}$$

Code radius is the working radius of the code disc's optical or magnetic patterning. When comparing performance between a Type B rotary sensor and an optical or magnetic encoder of similar size, the Code Radius is taken to be the average of the outer and inner radii of the sensor, to yield Equation 27.

Equation 27

$$Imbalanced\ Reference\ Sensitivity\ to\ Radial\ Misalignment = \frac{180°}{\pi} \times \frac{2}{(Outer\ Radius + Inner\ Radius\ )}$$

The Radial Misalignment Rejection Ratio can then be defined as in Equation 28. This compares measured performance to expected performance for an alternative encoder system that does not benefit from balance.

Equation 28

$$Radial\ Misalignment\ Rejection\ Ratio = \frac{Imbalanced\ Reference\ Sensitivity\ to\ Radial\ Misalignment}{Measured\ Sensitivity\ to\ Radial\ Misalignment}$$

8 Integrating PCB Designs

8.1 Sensor and Target PCB File Formats

Sensor and target PCB designs are provided as Gerber files. An AssemblyInfo layer includes specifications that must be met in order for parts to perform according to their datasheets. These include board stack-up and tolerances.

Sensor and target PCB designs are also available in Altium format, for customer convenience. This Altium version includes board stack-up details in the Layer Stack Manager. However these are only approximate nominal values. Please refer to the AssemblyInfo for specifications including tolerances. These should be communicated to the PCB manufacturer, to ensure the specifications are met in full.

8.2 Definition of Ovality

The PCB manufacturing process can introduce small imperfections in copper coil placement relative to the ideal locations specified in Gerber and Altium files. One of these imperfections is stretch error. Sensor and PCB designs are largely immune to stretch error when it is isotropic – the same in all directions in the plane of the PCB. However if the stretch is directional then small linearity errors can be introduced.

When stretch is directional, a feature or array of features that is circular in the original Gerbers becomes distorted into an ellipse (oval) shape once manufactured, as illustrated in Figure 25.

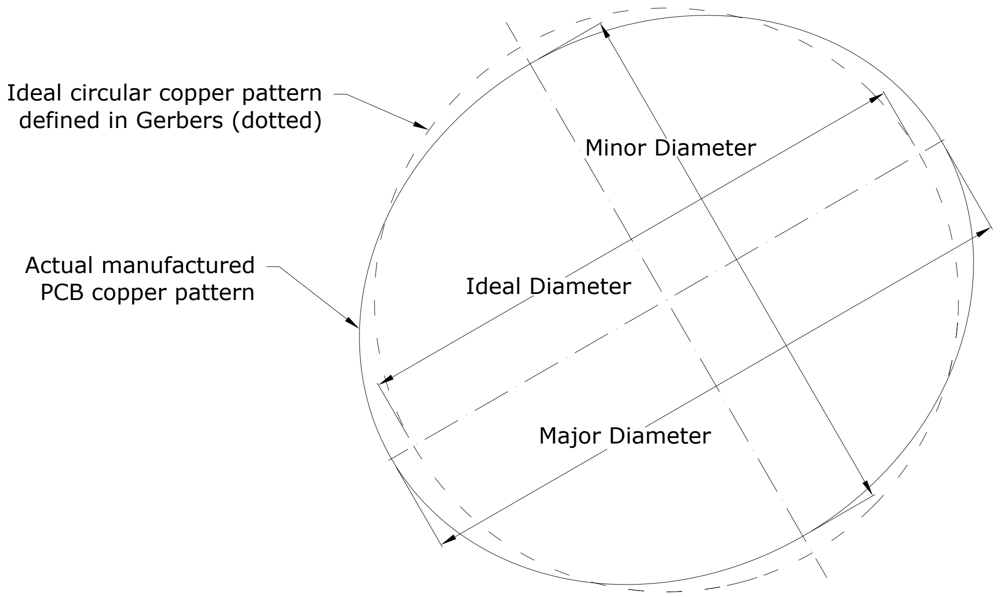

Figure 25 Definition of Ovality

The Ideal Diameter is the diameter of the original feature in the Gerber files. The Major Diameter is the diameter measured along the major axis of the ellipse, and the Minor Diameter is measured along the minor axis. Ovality is defined as follows…

Equation 29

$$Ovality\ /\% = 100\% \times \frac{(Major\ Diameter - Minor\ Diameter)}{Ideal\ Diameter}$$

PCB manufacturers do not normally specify Ovality limits for their process. Stretch error is normally more important to manufacturers and their customers, because it must be well controlled in order for vias to be drilled in the correct locations relative to copper traces. Nevertheless, Ovality has a small but measurable effect on sensor accuracy so it is included in specifications shown on the AssemblyInfo layer.

8.3 Making Connections Between Sensor and Electronics

Sensor PCB designs include a Sensor Coil Area where patterned coils excite and detect the rotating target. Connections are made to these coils at the edge of the Sensor Coil Area. The locations of these connections are specified in the sensor PCB's Gerber and Altium files, on the AssemblyInfo layer. Connections to both ends of each coil usually appear, as illustrated in Figure 26.

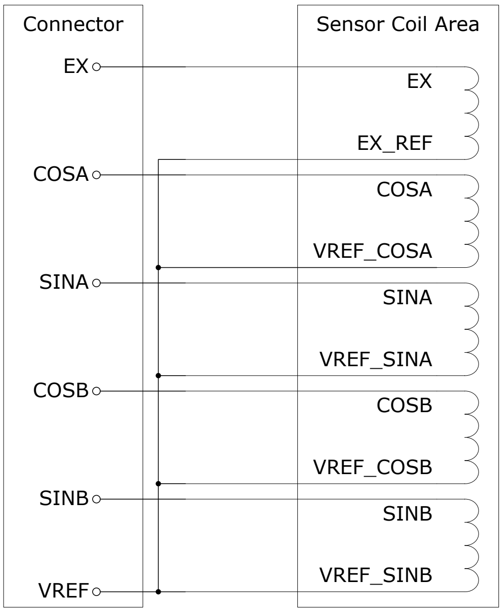

Figure 26 Sensor PCB connections between Sensor Coil Area and connector

The coil common returns (EX_REF, VREF_COSA, VREF_SINA, VREF_COSB, VREF_SINB) are connected to VREF outside the Sensor Coil Area.

If the sensor PCB design is to be modified by a customer to add Resonant Inductive Encoder IC circuitry on the same PCB, it is recommended to make this common connection to VREF inside this circuitry. This arrangement is illustrated in Figure 27. This is to allow the sensor connections to be routed in pairs, which helps minimise unwanted inductive coupling between each pair and the resonator and any interference sources.

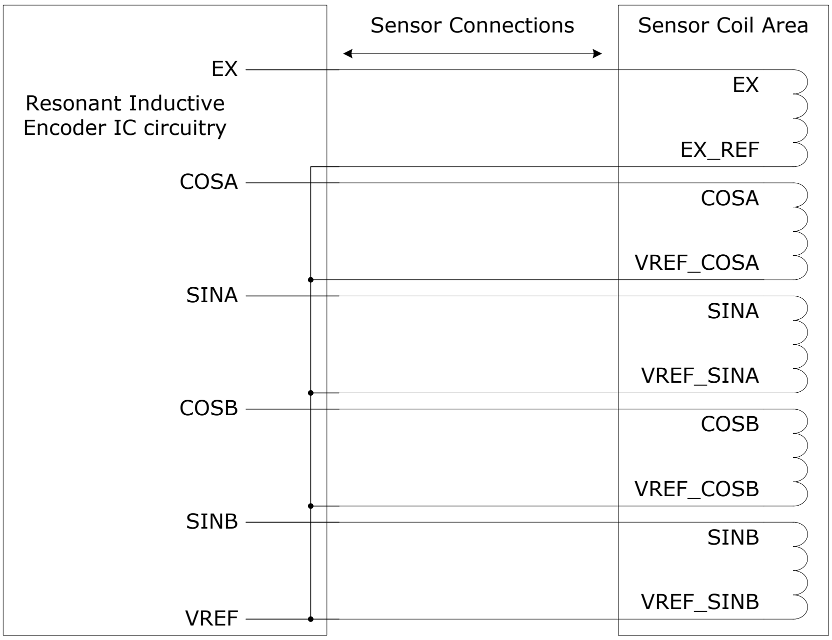

Figure 27 Customer PCB connections between Sensor Coil Area and circuitry

The loop area enclosed by each pair of sensor connections (EX and EX_REF, COSA and VRF_COSA, SINA and VREF_SINA etc) should be minimised. This means placing then next to one another on the same PCB layer with minimum gap in between, or on adjacent PCB layers as illustrated in Figure 28.

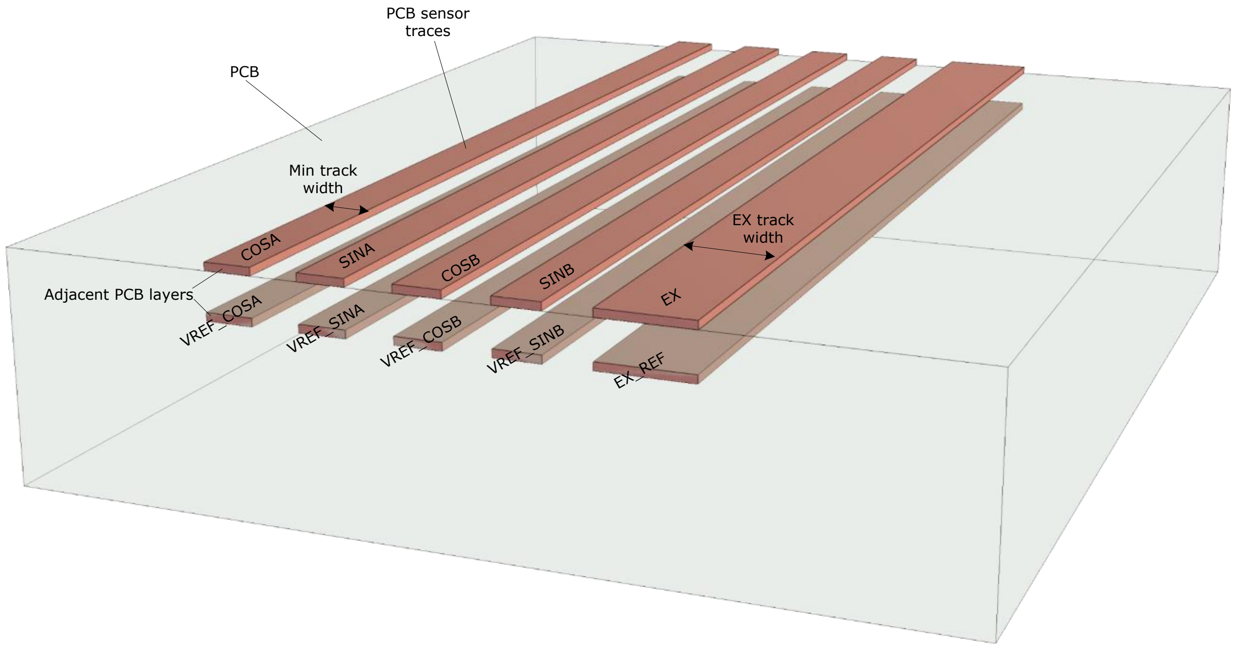

Figure 28 Sensor trace PCB connecting arrangement

It is not necessary for COSA, SINA and so on to be on the same PCB layer. They can be on different layers, providing their common return is either immediately adjacent on the same layer or in the same location on an adjacent layer.

The excitation coil's connecting tracks EX and EX_REF should ideally use wider traces, for example 0.4mm. This helps keep its resistance low and hence improves power efficiency slightly, and signal levels.

Connecting traces longer than 200mm should be avoided. For best performance keep them as short as possible. Measurements of performance quoted in sensor datasheets are taken with a 60mm connecting lead length between sensor and electronics unless otherwise stated.

8.4 Copper Thickness

It is important to check that sensor and target PCBs are manufactured with the correct copper thickness.

Sensor PCBs are typically manufactured using a nominal 35µm copper thickness on all layers ("1 oz per square foot"). This is a very typical copper thickness for PCB manufacture. It is thick enough to keep coil resistances low for efficiency, especially the excitation coil. However it is thin enough to allow the use of moderately fine track and gaps at high PCB manufacturing yield.

Target PCBs are typically manufactured using 70µm copper thickness on all layers ("2 oz per square foot"). This helps to keep trace resistances low, which is important for obtaining high Q-factor (see section 3.4). Trace widths are typically somewhat greater than those used for sensor traces, so that PCB manufacturing yield remains high.

PCB data sent to manufacturers must be carefully checked to ensure that the correct copper thickness and tolerance is specified.

9 Rotation Speed and Mechanical Stability

9.1 Disclaimer

CambridgeIC is responsible for the design of the target's resonator coils and its electrical design. It is the responsibility of CambridgeIC's customer to ensure that the target's mechanical design and manufacturing approach is suitable for their application. In particular, CambridgeIC's customer must ensure that all possible consequences of mechanical failure managed in a safe manner.

This section is for guidance only, to explain CambridgeIC's understanding and experiences.

9.2 Likely Mechanical Failure Mode

The target includes one or more SMD capacitors. It is these capacitors that are likely to limit the maximum rotational speed of the target, especially if the capacitors rely only on a solder joint and adhesion of copper to the PCB substrate to keep them in place. If the centripetal force applied to the capacitor through the solder and copper adhesive is large enough, it will come loose.

9.3 Centripetal Force and Acceleration

Figure 29 illustrates a target rotating about its axis with angular velocity ω. A capacitor with mass Mc is positioned at a radius Rc from the rotation axis. It experiences a centripetal acceleration Ac and centripetal force Fc.

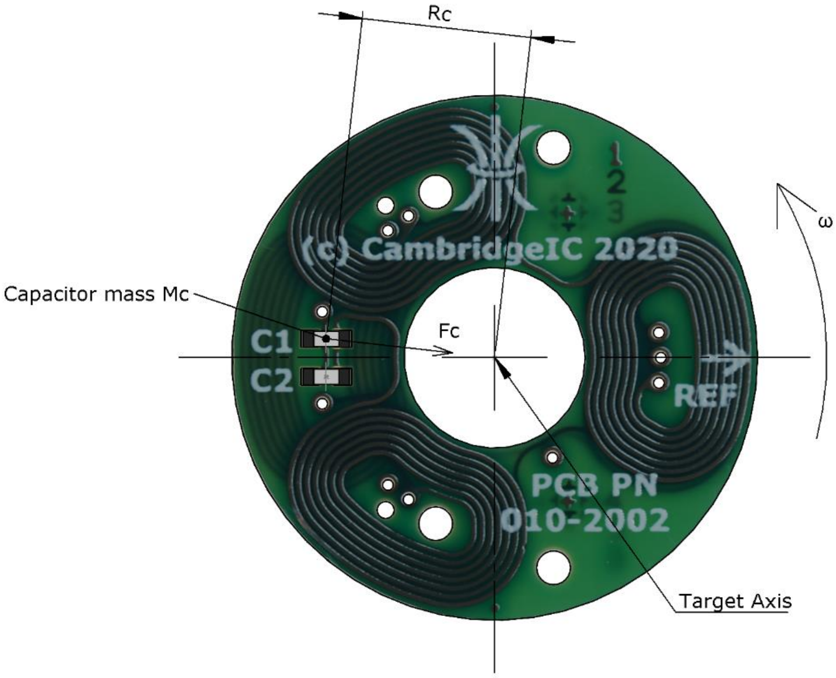

Figure 29 Centripetal force parameters

Angular velocity ω is expressed in radians per second and is related to revs per second and revs per minute by Equation 30.

Equation 30

$$\omega = 2 \times \pi \times revs\ per\ second = 2 \times \pi \times \frac{Revs\ per\ minute}{60}$$

The centripetal acceleration of the capacitor is given by Equation 31.

Equation 31

$$Ac = \omega^2 \times Rc$$

Note that centripetal acceleration is proportional to the square of angular velocity.

The centripetal force Fc acting on the capacitor is then given by Equation 32.

Equation 32

$$Fc = Mc \times Ac$$

If the capacitor were to come loose during rotation then its initial velocity Vc will be given by Equation 33.

Equation 33

$$Vc = \omega \times Rc$$

9.4 25mm B3 Target Example

Table 2 lists the mass and effective radius of the capacitor(s) used on the 25mm B3 target assembly, part 013-1037.

Table 2 25mm B3 target parameter values

Parameter	Value	Comments
Capacitor Mass Mc	13µg	Approximate mass of 0603 component
Effective radius of capacitor Rc	8.05mm	Nominal rotation axis to centre of mass

The part has been operated at 60,000rpm during informal testing at CambridgeIC. Table 3 lists calculation results for this rotation speed.

Table 3 25mm B3 target calculation results at 60,000rpm

Calculated value	Value	Comments
Angular velocity ω	6283 rad/s	At 60,000rpm
Ac	320000 m/s^2	=32000g, where g is acceleration due to gravity ~ 10m/s^2
Fc	4 Newtons	Equivalent to 400 grams force
Vc	50 m/s	Capacitor velocity at 60,000rpm

9.5 Comments on Mechanical Protection Measures

When a target is used with exposed capacitor, it is difficult to establish an operating speed at which the target will safely operate without mechanical failure, because relevant specifications such as solder and copper laminate shear limits are rarely published or tested by PCB fabs and assembly houses. Even if specifications were available, it would still be necessary to protect against possible harmful effects of unexpected failure.

It may be possible to increase the mechanical resilience of a target by securing the capacitor to the PCB with glue, for example a thin glob top of epoxy. This may help increase the maximum operating speed, but it does not eliminate the risk of failure at any given speed.

It is therefore essential that a target be protected with a guard or equivalent protective measures to catch debris in case it unexpectedly disintegrates.

10 Document History

Revision	Date	Comments
0001	5 Jan 2023	First draft
0002	23 October 2023	Added self capacitance of target coils CSELF to calculation of required resonator capacitor CCAPS.
0004	31 October 2024	Removed "CONFIDENTIAL"

11 Contact Information

Cambridge Integrated Circuits Ltd
21 Sedley Taylor Road
Cambridge
CB2 8PW
UK

Tel: +44 (0) 1223 413500

info@cambridgeic.com

12 Legal

Patents relating to the parts described in this datasheet are pending.