Inductive Sensor Design Principles

For use with the NCS32100

AND90191/D

Inductive position sensors are an alternative method to optical and magnetic encoders for measuring rotational position. Various types of inductive position sensors have been used for automotive applications but have typically been limited to accuracies that are not acceptable for industrial applications. Several improvements have been made by **onsemi** to the inductive sensor design that allows it to get to better accuracies while still maintaining the benefits of inductive encoding such as low sensitivity to contaminants and vibration. This application note summarizes the sensor improvements that are utilized by the NCS32100 to get better than 50 arcsec accuracies with extremely good repeatability using only PCBs for the rotor and stator.

BASIC PRINCIPLES OF INDUCTIVE SENSOR

Inductive position sensors operate on the basic principle of mutual inductance between 2 conductive loops. An AC current driven in one of the two loops creates a magnetic field that induces an EMF (or voltage) of the same frequency in the second loop. The induced voltage amplitude depends on the proximity and orientation of the second loop to the first. In an inductive position sensor, this principle is used to determine the angular position of a moving coil, called a "rotor" relative to a stationary coil, called a "stator". Inductive encoders are built using a rotor with passive coils placed in proximity to a stator with coils and electronics to measure the inductive coupling with the rotor. The images below describe how the inductive sensor works with an NCS32100 to measure position to high accuracy and at high speed. Figure 1 below shows all the pieces of an inductive sensor. The rotor is a single layer PCB with 2 passive coils on it. The inner loop is the rotor coarse loop. The outer loop is the rotor fine loop and the stator has 3 parts. The inner most pattern on the stator board is the coarse receiver coil set. The outermost pattern on the stator board is the fine receiver coil set. The coil in between the fine and coarse coil loops is the excitation coil. The functions of these will be explained individually.

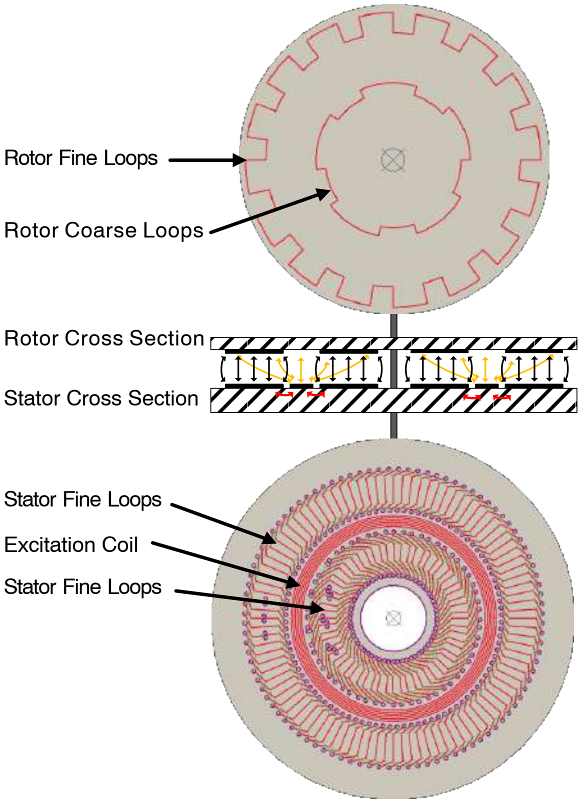

Figure 1. Anatomy of an NCS32100 Inductive Sensor

Figure 2 shows an overlay of the rotor fine and coarse passive coils (in blue), and the excitation coil that is on the stator board (in red). Both the fine and coarse passive coils have segments that are parallel to the excitation coil. The excitation coil is driven at around 4 MHz by the LC oscillator pins on the NCS32100. These parallel segments will inductively couple with the excitation coil and a 4 MHz AC Eddy current is induced in both the fine and coarse rotor coils.

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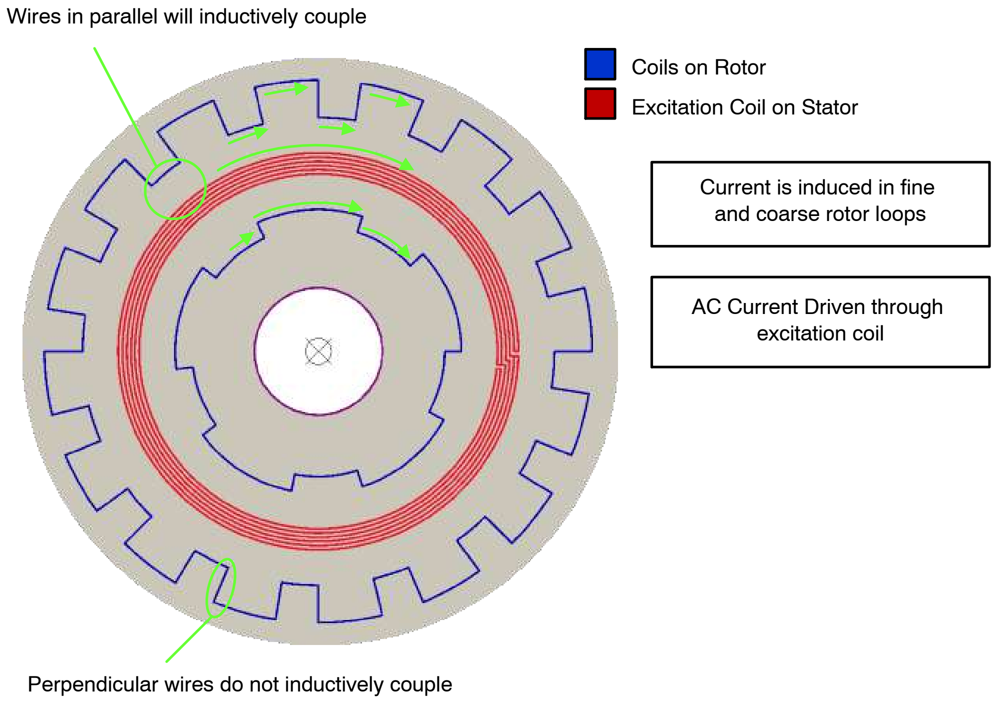

Figure 2. Rotor Overlaid with Stator Excitation Coil

Figure 3 below shows the rotor fine and coarse passive coils (in blue) overlaid with the stator fine and coarse receiver coils (in red and green) for comparison. As seen in the figure, the radial segments of the receiver coils are in parallel with the lateral segments of the rotor passive coils. Since the rotor coils have a 4 MHz Eddy current flowing in them, the parallel segments in the receiver coils will inductively couple the 4 MHz from the rotor. As the rotor turns, the parallel segments between the rotor and the stator will be stronger when the segments are aligned in proximity and weaker when the segments are not aligned or are further away.

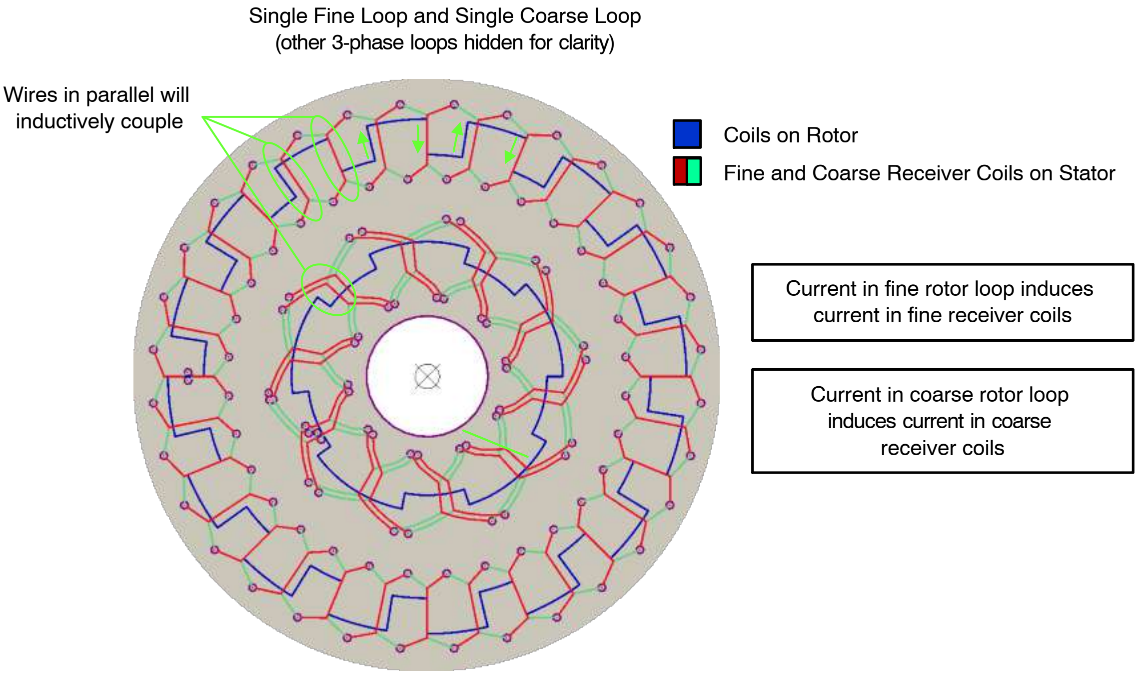

Figure 3. Rotor Passive Coils Overlaid with Stator Fine and Coarse Rotor Coils

As the rotor turns, this creates an amplitude modulation on each of the receiver coils (as shown in Figure 4). Each receiver signal will be offset in phase by 120 degrees if the coils are arranged in a 3−phase pattern. The NCS32100 REC pins connect to the receiver coils. The coarse and fine receiver coils are arranged and interleaved in a 3−phase orientation.

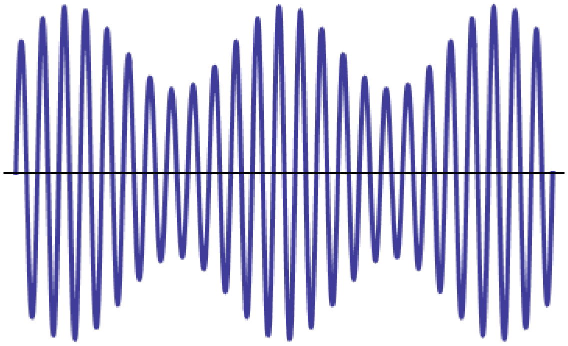

Figure 4. Amplitude Modulated Voltage Signal as Seen at a REC Pin on the NCS32100

The resulting receiver signals follow the formula:

$$V_{rec_i}(\theta, t) = V_{ex} \sin(2\pi F t)\left(DirectCoupling_i + Airgap \times RotorCoupling\left(N\theta + \varphi_i\right)\right) \quad \text{(eq. 1)}$$

Where:

- V_{ex} is the excitation coil amplitude.
- F is the excitation frequency.
- *DirectCoupling* is a constant caused by a parasitic mutual inductance coupling between the excitation coil and the connections between the electronics and the fine and coarse receivers.
- *Airgap* is a factor that decreases as the vertical separation between the rotor and the stator increases.
- *RotorCoupling* is periodic function where N is the rotational symmetry of the receiver coil and phi the phase shift between receiver coils on the stator.

These modulated 3−phase receiver coil signals are used by the NCS32100 to calculate position, velocity, and acceleration.

There is parasitic coupling on the stator that cannot be avoided. The coupling happens between the excitation coil the electrical connections for the fine and coarse receiver signals. The main areas that cause this parasitic coupling are circled in green in Figure 5 below. This parasitic coupling results in unwanted offsets in the receiver coil signals. This parasitic coupling is called “direct coupling”.

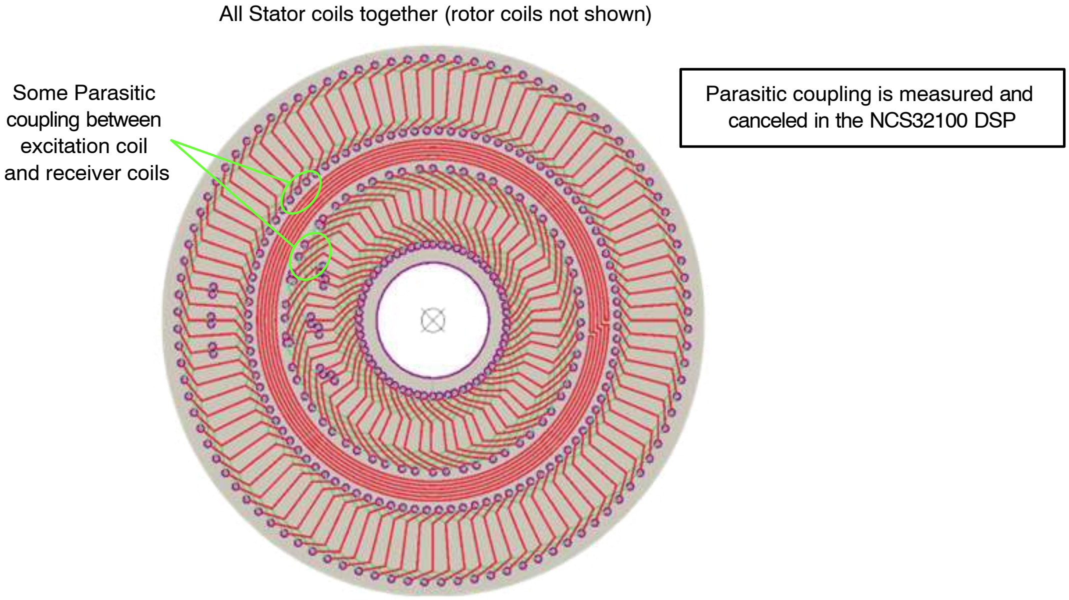

Figure 5. Areas Where Parasitic Coupling Occurs between the Excitation Coil and the Receiver Coils on the Stator

To compensate for offsets in the receiver coil signals (due to parasitic coupling between the excitation coil and the receiver coils) an attenuated version of the excitation signal is fed into the NCS32100. This is derived by means of a capacitive divider from the LC pins on the NCS32100. The direct coupling offset signal can also be created by putting a witness coil on the stator to couple with the excitation coil the same way that the receiver coils couple with the excitation coil. This witness signal is demodulated in the NCS32100 and provides a direct coupling offset that can be used for compensation of the unwanted parasitic coupling.

HARMONIC DISTORTION REDUCTIONS

The excitation coil is driven at 4 MHz, but the frequency is irrelevant because synchronous demodulation is used. The receiver coil signals are demodulated in the NCS32100 by the same frequency that is used to drive the excitation coil. After the carrier frequency is removed through demodulation, and the direct coupling is compensated, the ideal coupling from the rotor should be a pure sine wave function of the rotor angle. Unfortunately, harmonic distortion is inherent to all inductive sensors. These harmonics limit the position accuracy that can be achieved by the inductive sensor. The carrier frequency is removed through demodulation in the NCS32100. Ideally the only remaining frequencies would be that associated with the movement of the rotor (Nf electrical periods per 1 full rotation of the rotor and Nc electrical periods per 1 full rotation of the rotor, where Nf is the number of loops in each fine coil and Nc is the number of loops in each coarse coil). Without applying proper techniques (patented by **onsemi**), harmonics at N*(2, 3, 4, 5, 6, 7, and beyond) will reduce the accuracy of the system. The NCS32100 is designed to leverage several techniques to reduce or eliminate these harmonics.

Twisted Loop Receiver – Eliminate Second Harmonic (and all even harmonics)

All even harmonics can be eliminated by designing the coil loops in such a way that they twist and double back on each other. Figure 6 below shows how this would be implemented for a 4−period sensor. The connections between the clockwise and counterclockwise loops are on the right side. The twist and double back is done in a way that preserves the correct current polarity in the sensor lateral traces. The current direction in each lateral is the same for both overlapped loops. This is important, since lateral currents in opposing directions would cancel out. The rotor traces are shown in grey, while the clockwise and counterclockwise stator loops are shown in red and green. The clockwise and counterclockwise arrows show the direction of the eddy current in the rotor and the coupling to the stator loops.

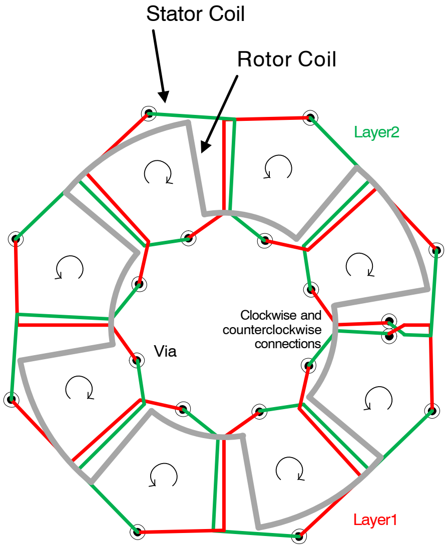

Figure 6. Twisted Receiver Coil Configuration

Advantages of 3−phase Inductive Sensors – Increase SNR

Drawing three receiver coils in a 3−phase Y configuration and measuring the voltage differentially between two phases will cancel the harmonics multiple of 3 N* (3, 6, 9, and beyond). In such systems the coils' fundamental amplitudes are shifted by $2\pi/3$ and the harmonics 3 have all the same phase ($3 \cdot 2\pi/3$). The differential measurement increases the immunity to external electro−magnetic interferences as the far−field EM disturbance picked up by one coil will be cancelled by the second coil as it is measured in anti−series with the first one. Figure 7 below shows how the 3−phase coils are connected to the receiver pins of the NCS32100 to achieve differential signal measurement. The 3−phase plot shown is the result of demodulation of the differential measurements while the rotor is moving at a constant velocity (showing measurements over one electrical period of the rotor). This 3−phase waveform is what is digitized by the NCS32100 internal ADCs and sent to the DSP block for position calculation.

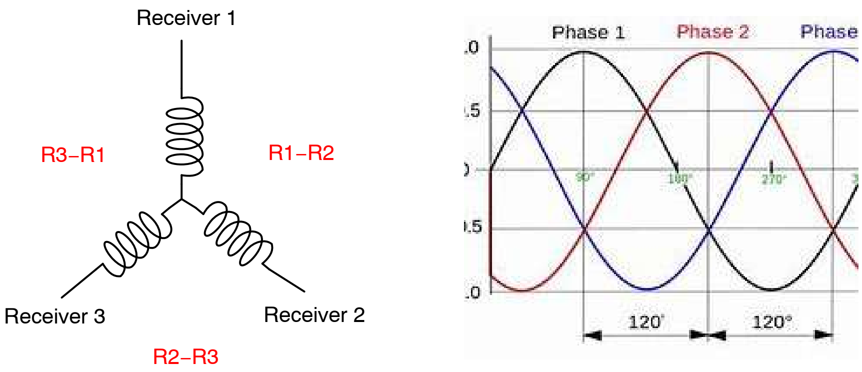

Figure 7. 3−phase Coil Orientation with Differential Measurement

Offset Distance on Rotor Periods – 5th Harmonic Reduction

The 5th harmonic can be reduced significantly by offsetting the rotor periods by a 1/5th multiple. For a 4−period sensor (as shown below) the offset to reduce the 5th harmonic would be 2/5*90 or 3/5*90 as one period is 90 degrees. The 2 and 3 5th possibilities allow us to draw the rotor with two interleaved loops as shown on Figure 8. This gives us another degree of freedom as we can slightly offset one loop versus the other. In the example below the offset is ½ of the 11th geometrical harmonic. The NCS32100 allows for 3 period coarse sensors and 5 period coarse sensors. For the 3−period case the offset would be 2/5*120 and 3/5*120. For the 5−period case the offset would be 2/5*72 and 3/5*72. The repeated inner rotor coil is for the reduction of the 11th harmonic. It is offset by 1/22*(360*Coil Periods). These methods work together to eliminate or reduce the harmonic distortion allowing NCS32100 sensors to be high accuracy. Sensor enhancements can be made at no additional cost and are protected by several **onsemi** patents.

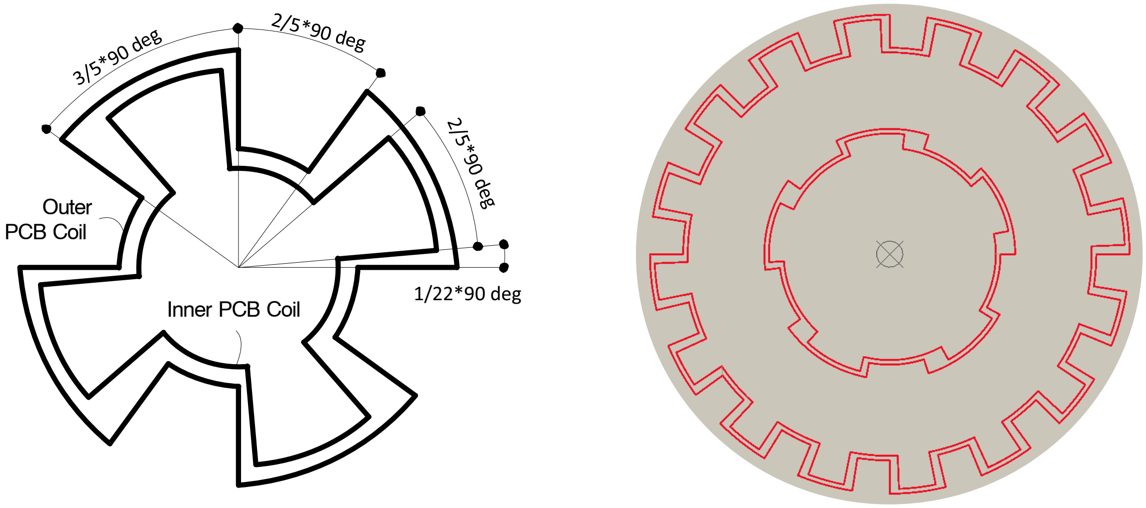

Figure 8. Rotor Period Offset to Reduce the 5th Order Harmonic Distortion (Full Rotor Design for a 16−period Fine Coil System and a 5−period Coarse Coil System)

SENSOR MECHANICAL ALIGNMENT

Ideally, the rotor and stator would be aligned perfectly with no eccentricity and perfect planarity. This is difficult to achieve due to mechanical tolerances that exist in a real manufacturing environment. There are 2 calibration methods that the NCS32100 supports to calibrate out any repeatable error that may exist due to PCB sensor asymmetries and mechanical alignment imperfections. The first calibration method is a self−calibration that is run internally to the NCS32100 and does not require an external reference like a precision encoder or a constant speed motor. This self−calibration takes samples as the rotor turns and adjusts 16 calibration coefficients to reduce the effect of asymmetries in the PCB sensor design. The second calibration method reduces any single period 360−degree or low geometrical frequency errors that is caused by some combinations of mechanical misalignment.

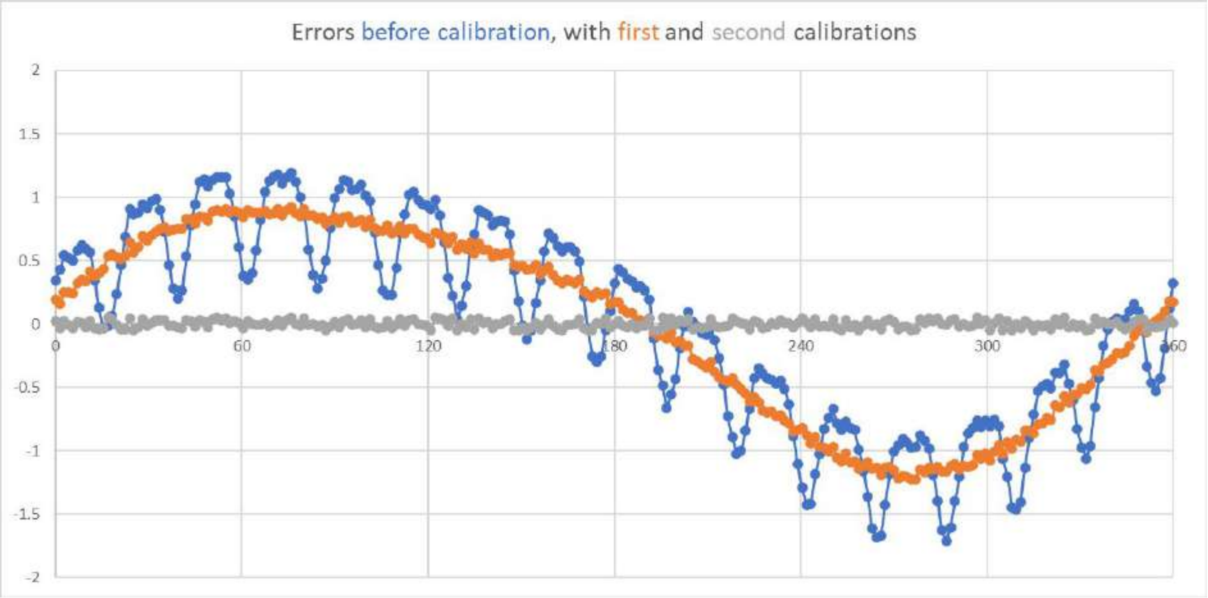

Figure 9. Errors before Calibration, after Self−calibration, and after Secondary Calibration

This calibration may not be needed depending on the nature of the mechanical misalignment. The second calibration method requires an external reference encoder and allows the user to program 16 coefficients used to linearize the position outputs from 0 to 360 degrees. The NCS32100 Reference Design Manual and the NCS32100 Datasheet cover the calibration options in more detail. Figure 10 below shows the different types of mechanical misalignment that can occur between the rotor and the stator. Inductive sensors use inductive coupling over the full surface of the rotor and stator (rather than just one point of measurement) to derive the current position. Because of this, they are inherently more robust against vibration, and reasonable amounts of mechanical misalignment. Mechanical misalignment including off−axis eccentricity, rotor to stator tilt, rotor to shaft skew, and rotor to stator wobble do not require calibration with an external reference encoder to compensate. Certain combinations of these will cause a 360−degree single period accuracy error that can be compensated for using the secondary calibration method. If the mechanical alignment can be designed to mitigate the combinational types of misalignments, then high accuracy can be achieved without additional calibration using an external reference encoder.

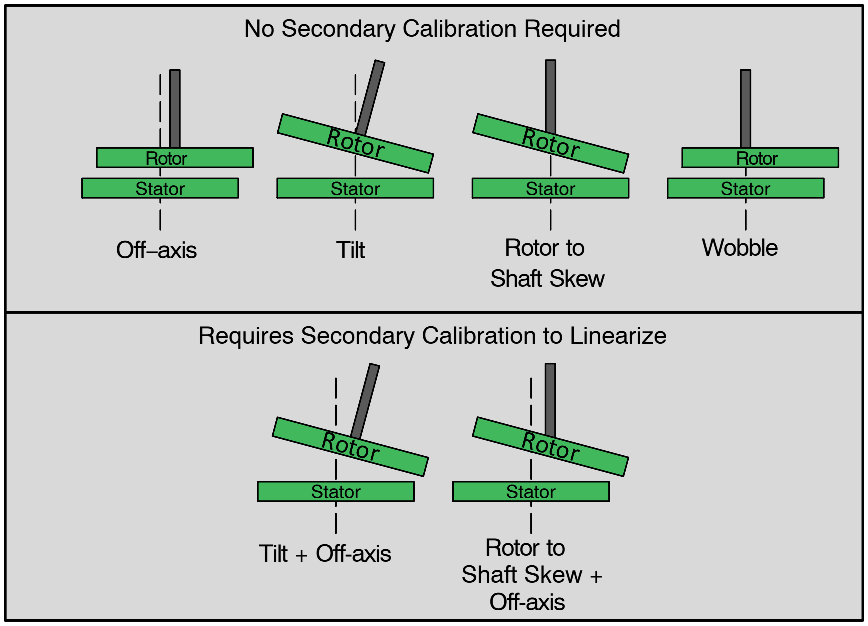

Figure 10. Mechanical Misalignment Error Classification

Figure 11 below shows the results of a well aligned stator and rotor using the NCS32100 and a 38 mm diameter sensor (64 period fine coil layout with 5 period coarse coil layout). The self−calibration was able to effectively remove the error caused by PCB asymmetries. The single period 360−degree error that is still present suggests that there is still some combinational misalignment. Because this error is repeatable, it could be removed if desired using the secondary calibration technique with an external reference encoder. The resulting accuracy would be on the order of ±5 arcsec.

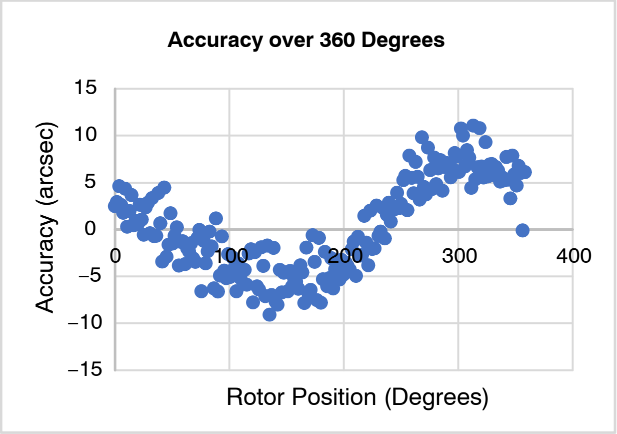

Figure 11. Example of Accuracy Test Data from the NCS32100 using a 64 Period 38 mm Diameter Sensor with No Secondary Calibration Performed

Airgap Variation

Sensor to sensor airgap variation is handle by means of automatic gain feedback in the NCS32100. If the airgap is larger than the optimal value, then the NCS32100 will automatically detect that the receiver coil signals are attenuated, and it will add gain to maintain dynamic range. If the airgap is smaller than the optimal value, then the NCS32100 will automatically detect that the receiver coil signals are too large, and it will lower the gain to prevent signal clipping. This allows the NCS32100 to operate over a wider range of airgaps. The typical airgap and min to max range depends on the specific sensor design. The NCS32100 38mm diameter reference design sensor was designed for a typical airgap of 0.5 mm, but sensors targeting larger airgaps are possible.

CONCLUSION

The NCS32100 leverages specific sensor design techniques to reduce harmonic distortion and increase accuracy for PCB inductive sensors. Mechanical misalignment will affect the overall accuracy of the system, but the NCS32100 provides features to calibrate out any repeatable errors caused by misalignment. This design allows inductive position sensors to reach better accuracy than was previously possible, making the NCS32100 a great solution for a robust rotary or linear position sensor.

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