Low Cost Planar Coil Structure for Inductive Sensors to Measure Absolute Angular Position

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***Abstract*—There are many applications that need to sense angular displacement/position, such as automotive electronic steering system, throttle and brake pedal position, motors, robotic arm, etc. Contactless sensors are becoming increasingly popular in these kinds of applications due to their robustness, reliability and longevity. The paper proposes a new contactless variable reluctance (VR) resolver that can be built on a PCB as coil traces. The coil layout consists of an excitation coil and two sense coils laid on a single plane of a PCB. A circular metallic disk with a sector aperture alters the induced voltage in the sense coils. The induced voltage in the sense coils is a sine and cosine function of the angular position of disk. The absolute angular position can be measured with high resolution based on sense coil voltages. The design is validated using an ASIC to process the sensor signals and compute the angular position. The linearity of the coil design has been validated through experimental results.**

Keywords-position sensor; VR resolver; planar sensor; inductive sensor, contactless sensor

I. INTRODUCTION

The reliability requirements of position sensing systems are stringent in some industries. While potentiometers offer a relatively inexpensive solution, they are susceptible to the effects of tough environmental conditions and can fail due to wear and tear effects. These problems have been overcome by non-contact sensors. Non-contact sensors are based on inductive, capacitive, optical, hall effect or magneto-resistive principles. Optical sensors face problems from dust, lubricant etc, while hall effect sensors may not work in an environment with disturbance from stray magnetic fields. Inductive position sensors are immune to magnetic and environmental conditions..

The inductive position sensor or resolver comprises of one or more excitation coils, and multiple sensing coils. The excitation coils are excited, and a voltage is induced in the sense coils due to mutual magnetic coupling. A conductive target that is positioned near the excitation and sense coils can change this mutual magnetic coupling relative to the position of the rotatable target. This can result in a change in the induced voltage in the sensing coils. This time varying voltage within the sensing coils can be measured and processed to determine the angular position of the target. As the sensing principle is based on high frequency, stray magnetic fields will not impact position measurement.

PCBs (printed circuit board) with inductive coil traces have been used in inductive sensors because it is cost effective to design coil layouts compared to traditional axial windings on a ferro-magnetic core. Planar windings have been designed in PCBs in earlier work [1]-[7]. Unlike most of these coil designs, the coil structure proposed in this paper can be etched on a single layer of a PCB. The rotating target is a disk made from thin sheet of metal. This reduces the total cost of the system and allows easy scalability.

The design described in [4] requires a slotted target, has 4 primary windings in sinusoidal arrangement, with two secondary windings. The primary windings are sinusoidally arranged, while the sense coils are arranged in the periphery. In the design described in this paper, the primary windings are arranged in periphery.

It is possible to design a linear position sensor based on inductive sensing coils and these are described in [6] and [8]. While the designs described in these papers use a target with coils on a PCB, the design described in this paper corresponds to a rotary position sensor whose target is a solid conducting metal plate.

The design suggested in [9] has four terminals, with windings of one line adjacent to each other and with the exciter coil forming a spiral under the sensing coils. The moving target used in the design is a circular PCB with copper bars on the periphery. The design described in this paper has windings of one sense coil opposite to each other, thus exhibiting better symmetry. It also has one end of each coil connected to ground, and the exciter coil runs on the periphery of the four sense coils. The moving target used in this design is circular and not rectangular.

The design described in this paper has been tested with Microsemi LX3301A inductive sensor interface device [10]. The device integrates an oscillator circuit for excitation, demodulation circuit with anti-aliasing filter and phase detection to process sensed sine and cosine signals. The built-in 32 bit processor computes the angle based on sine and cosine signals.

II. SENSOR DESIGN AND OPERATION

The operating principle of proposed planar angular position sensor is the same as that of a Variable Reluctance resolver (VR resolver). The structure consists of an excitation coil and two sensor coils formed by planar structure on a PCB. The structure also consists of a circular rotatable inductive coupling element comprising a sector aperture. The rotatable inductive coupling element is positioned in overlying relation to the planar excitation coil and separated by an air gap. The inductive coupling element can be any conducting material such as copper, aluminum or iron.

The excitation coil is wound in a planar circular manner with one or more turns. The sensor coils SC1 and SC2 are positioned within the excitation coil as shown in fig. 1. Each of the two sensor SC1 and SC2 coils has clockwise winding portions *C1+ and C2+* placed diametrically opposite to a counter-clockwise winding portions *C1*- and *C2*-. The sensor coils can have one or more number of turns on each of the clock wise and counter-clock wide directions. But the number of turns on clockwise winding should be equal to those on counter-clock wise winding.

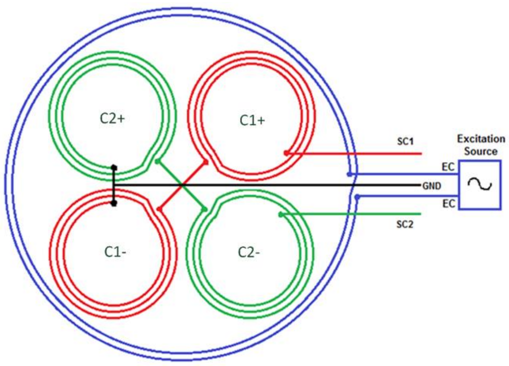

Figure 1. Coil layout.

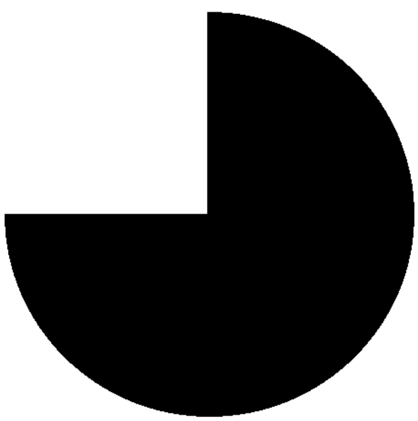

Figure 2. Circular disk with a sector aperture – one quarter cut out.

When an alternating current of sufficiently high frequency, greater than 1 MHz, is injected into the excitation coil, it generates a time varying magnetic field. As the sensor coils are placed within the excitation coil on the same plane, the time varying magnetic field induces voltage in the sense coils due to mutual coupling. The sense coils are geometrically placed in such a way that the mutual coupling is same for both the sense coils and for clockwise and counter-clockwise portion for each coil. Due to this, the amount of voltage induced in clockwise and counter-clockwise portion cancel out each other when there is no external disturbance. The resultant voltage in each of sense coils SC1 and SC2 is zero.

When a sheet conducting material is introduced in to the time varying magnetic field generated by the excitation coil, eddy currents are induced in the conducting material. Also, according to the electromagnetic wave propagation theory, the electromagnetic wave can be reflected by the metallic disk. These two effects will dampen the magnetic flux flowing into the sense coils in the region where the conducting material is placed and reduce induced voltage.

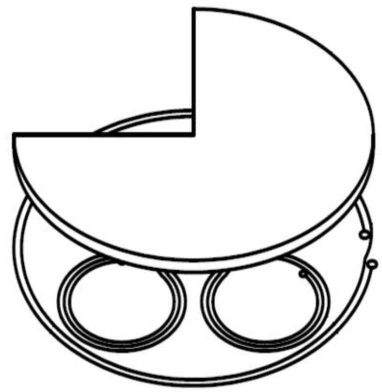

Figure 3. Angular position measurement setup – three dimensional view.

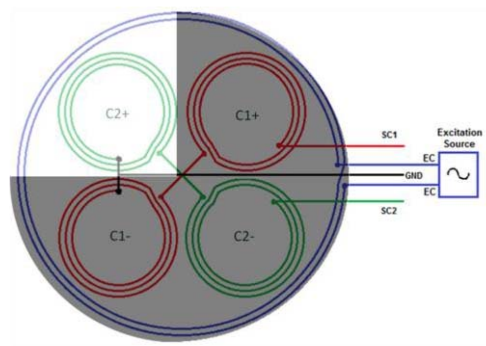

Figure 4. Angular position measurement setup – two dimensional view.

For the proposed angular position measurement system, a conducting sheet in circular form (disk) with a sector aperture ($1/4^{th}$ of the disk cut out) is used as shown in fig. 2. This disk, hereupon called target, is attached to a shaft whose angular position has to be measured and placed on top of coil assembly concentric to the excitation coil as shown in fig. 3 and fig. 4. When the target is at 0^0 position as shown in figure, the conducting portion of the target covers *C1+* and *C1*- equally and the resultant voltage in SC1 is zero. But for SC2, *C2*- is completely covered by metal sheet and *C2+* completely uncovered. This will result in the voltage in *C2+* being higher than *C2*- and SC2 will have effective positive voltage (in phase with excitation coil voltage). Hence at 0^0 position, SC1 has zero voltage and SC2 has maximum positive voltage.

The excitation source injects high frequency current in to the excitation coil. The peak amplitude of the high frequency current is controlled through the source. If I_{max} is the peak amplitude of the exciter current, and ω is the frequency of current in the exciter coil, then the exciter current is expressed as

$$I_E = I_{max} * \sin(\omega t) \tag{1}$$

The voltage induced in the sensor is represented by (2), where M is the mutual inductance between the sense coil and the exciter coil, and θ is the angular position of the target disk. By replacing the exciter current in (2) with (1), we get (3).

$$V_{SC} = M \frac{dI_E}{dt} \tag{2}$$

$$V_{SC} = M * \omega * I_{max} * \cos(\omega t) \tag{3}$$

The mutual inductance of the sense coils is a function of the angular position of the target. This is represented as shown in (4) and (5).

$$V_{SC1} = M \sin\theta * \omega * I_{max} * \cos(\omega t) \tag{4}$$

$$V_{SC2} = M \cos\theta * \omega * I_{max} * \cos(\omega t) \tag{5}$$

As the target rotates, the voltage induced in sense coils changes as a sinusoidal and co-sinusoidal function of target angular position as shown in fig. 5.

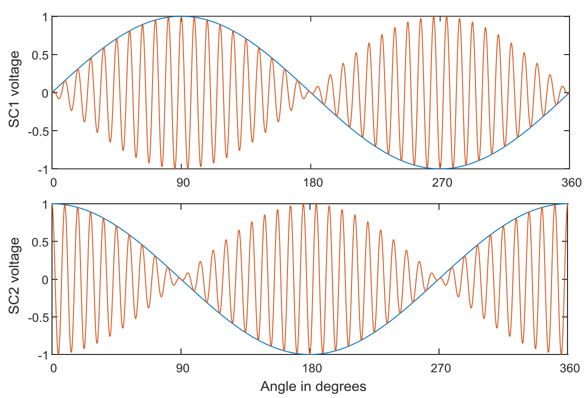

Figure 5. Voltage induced in sense coils.

III. IMPLEMENTATION

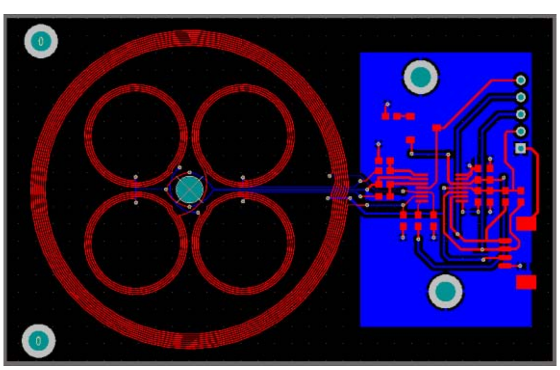

Figure 6. PCB layout of the angular position measurement setup.

The coil assembly and the demodulation circuit to compute angle from the sense coil voltages is implemented on a two layer PCB. The excitation and sense coils are laid on the top layer and bottom layer is used only for routing the coil terminals to the demodulation circuit as shown in fig. 6. Fig 7 shows the PCB fabricated with the coil layout described in the previous section.

Figure 7. PCB fabricated for angular position sensing with parts populated.

The Microsemi LX3301A inductive sensor interface device is used to source the currents through excitation coil and demodulate the voltage signals from sense coils. The excitation coils circuit is based on cross coupled LC oscillator that uses two inductors and two capacitors. The two inductors of the LC oscillator are formed by the excitation coil and capacitors are soldered on the board to get required resonant frequency. A metallic disc with a thickness of 0.2mm with a cut-out sector aperture is used as a target. Table 1 lists the coil parameters and values.

LX3301A uses analog frontend as shown in figure to demodulate the resonant frequency signal from sense coils using phase detection. The demodulated wave is then passed through ADC and processed by a built-in 32 bit MCU to compute the angle. The internal DAC in the ASIC converts the computed angle into analog voltage that varies from 0V to 5V for 0^0 to 360^0 of angular position. The block diagram of the LX3301A is shown in fig. 8. The schematic of the device with the coils is shown in fig. 9.

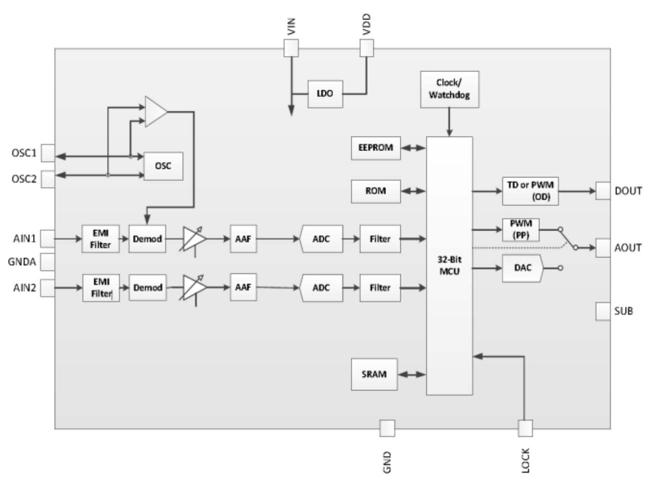

Figure 8. Block Diagram of LX3301A.

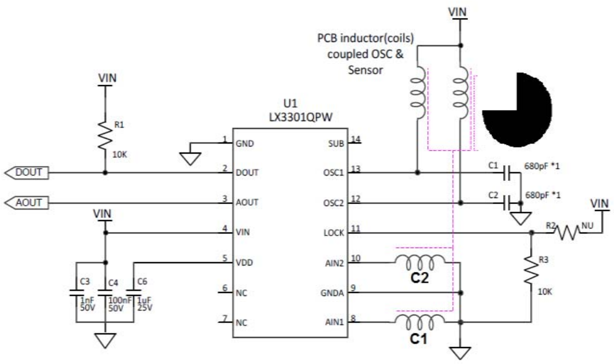

Figure 9. Schematic of the sensing circuit.

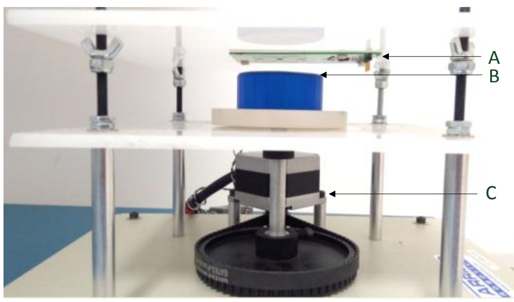

Figure 10. Stepper motor based setup to provide controlled angular position – (A) is the PCB with coils, (B) is the platform on which the target is placed and (C) is the stepper motor which produces controlled angular displacement.

IV. Experimental Results

The setup depicted in fig. 10 is used to validate the coil design. It contains a stepper motor to produce controlled angular position. The stepper motor increments the angular position by 3^0 and data is collected at each position. The collected data includes the sine and cosine signal magnitude from ADC, reference angular position and measured angular position. The data is collected by using SENT protocol feature available in LX3301A. Fig. 11 shows the coil voltages as observed at the ADC inputs and Fig. 12 shows a graphical representation of test data collected using the SENT protocol, where the demodulated sine and cosine waves are shown in blue and green, while the calculated rotor position is shown in pink.

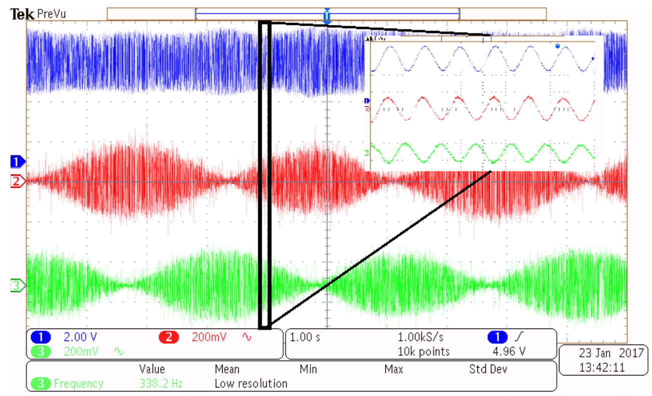

Figure 11. Coil voltage waveforms observed on scope – inset shows the high frequency excitation waveforms and the corresponding coil voltages.

TABLE I. Coil Parameters

Parameter	Value
Excitation coil diameter	45mm
Sense coil diameter	15mm
Resonant frequency	3.2 MHz
Target diameter	45mm
Target distance (airgap)	10 mm

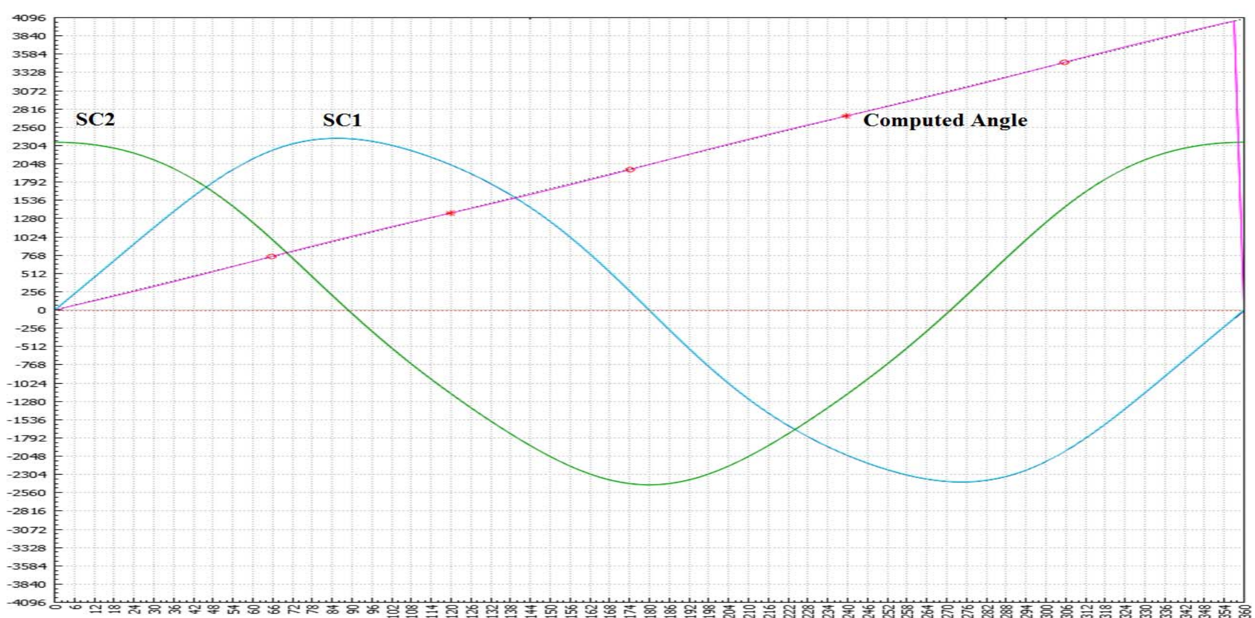

Figure 12. Data collected from the LX3301A device – SC2 (green), SC1 (blue) and angle plots (pink).

V. CONCLUSION

A low cost scalable planar coil structure is proposed for measuring absolute angular position. The proposed coil layout is implemented on a two layer PCB and a thin disk of steel is used as target. An inductive sensor interface device from Microsemi is used to validate the proposed design. The experimental results show that the coil structure exhibits linear response to position variation.

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