Development of a Flexible Printed Circuit coil based Inductive Proximity Sensor

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ABSTRACT

In this publication a method for design and validation of a Flexible Printed Circuit coil based Inductive Proximity sensor is explored. The sensor design uses a coil constructed with copper traces on a flexible polyamide base, with a ferromagnetic material disk on one side for magnetic shielding. Initial coil specifications are developed using mathematical expressions for circular spiral coil inductors in air, then Finite Element Analysis is used to determine the deviation of magnetic properties created by introduction of the ferromagnetic disk. The magnetic characteristics of the coil assembly is then superimposed against a simple mathematical model of an inductive-capacitance tank circuit and validated against a pre-specified electrical system based on an Texas Instruments™ Analog Front End integrated circuit. Furthermore, the results are then used to determine the sensor performance characteristics including detection range and resolution.

INTRODUCTION

Inductive proximity sensors are a staple of the modern industrial and consumer automation. It is the most reliable and proven way to detect the presence and position of a metal object in any kind of mechanism. Traditionally inductive proximity sensors use an Inductive-Capacitive (LC) tank based detection circuit, where the oscillation frequency of LC tank is varied by the inductance change of a coil introduced by a metal target, and an electronic circuit is used to detect the frequency change. Figure 1 shows a simplified diagram of the traditional design.

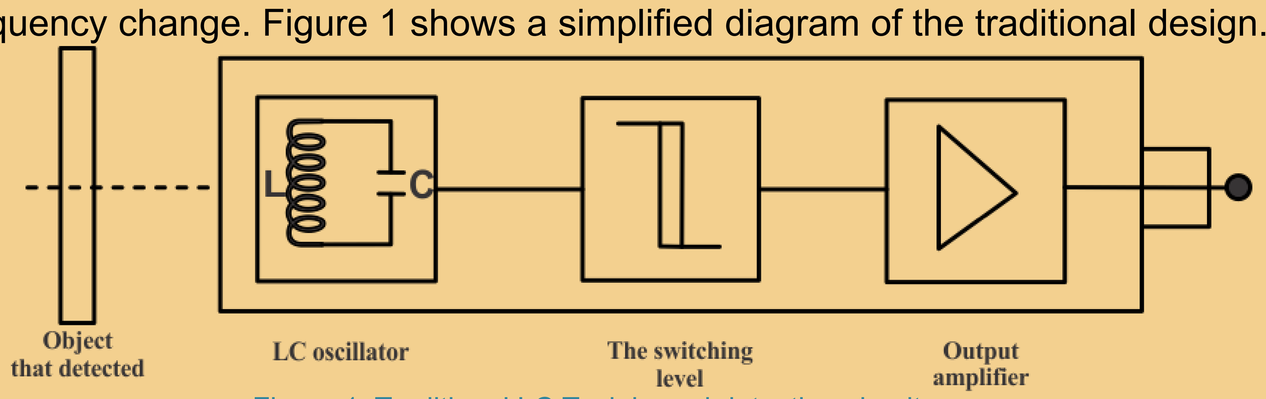

Figure 1: Traditional LC Tank based detection circuit

Currently available inductive proximity sensors use a coil made of Litz Wire wound around a magnetic core material to construct the Inductor element in the above LC Tank oscillator[1]. The traditional construction methods for these sensors are time consuming, costly, and uses multiple fabrication steps resulting in more rejected parts, and requires more precision in mechanical constructions. In modern applications, alternative construction methods using planar PCB based coils are being adopted[2]. This PCB based constructions uses a planar spiral coil directly etched on a rigid printed circuit board which acts as the inductor in the LC tank. Usually the other electronic components are placed on the same PCB, or a connector is used to interconnect the PCB to a separate motherboard. Additionally, modern Inductive Proximity Sensors are more and more using methods other than just detecting change of frequency for target sensing. One of the methods include detecting the eddy current losses in the coil using parallel or electrical models[3] shown in Figure 2.

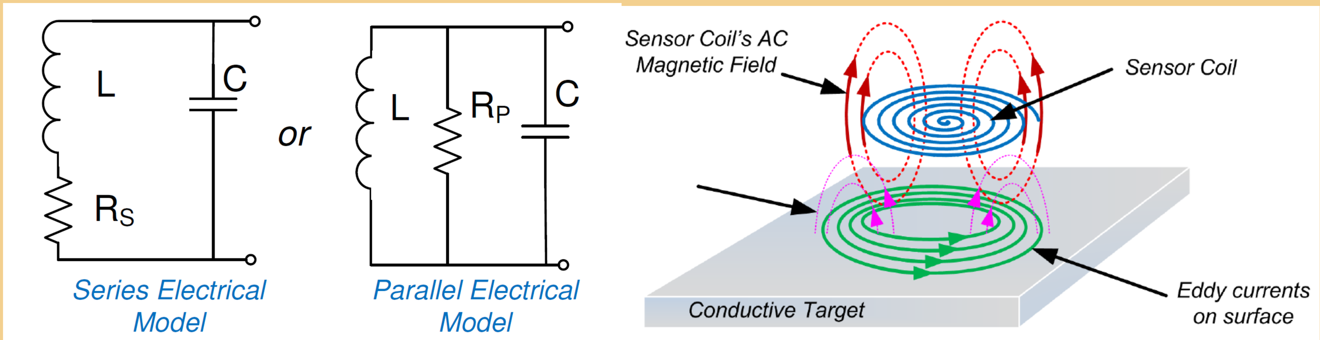

Figure 2: Parallel and Series electrical model of Eddy current losses on a spiral electromagnetic coil

But current PCB based construction has a few shortcomings. The planar electromagnetic coil creates magnetic fields in both surfaces of the PCB, which limits the orientation and assembly options for the sensor. Also the requirements of having connectors or other circuit component on the rigid PCB limits the sensor sizes and form factor.

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In December 2019, Midwest Energy Resource Consortium (M-WERC) in partnership with Eaton Corp. have arranged a tech challenge to develop a new construction method to address those shortcomings in both wire-wound and planar coil based designs.

We have developed a novel construction method of such planar coil based Inductive Proximity Sensor to address those shortcomings. Our method uses a flexible printed circuit to fabricate the planar coil, connecting cable and connector in a single fabrication process. Additionally It uses a ferromagnetic disc placed behind the coil to shield one side of the sensor from magnetic fields.

METHODOLOGY

Initially, preliminary design specifications of the planar coils are derived using a target frequency and inductance range required by [4] the Texas Instruments™ LM9100 AFE for inductive proximity sensors. For that we used Mohan's equations [5] to find the parameters of a planar spiral coil in air. A online tool [6] developed by Texas Instruments™ was used to speed up the process.

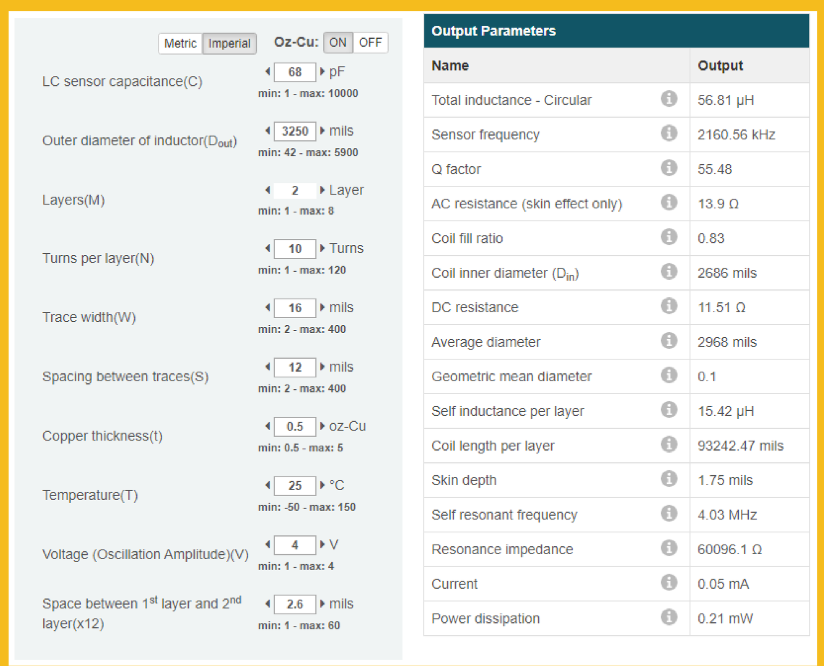

Figure 3: TI WEBENCH® Coil Designer Parameters

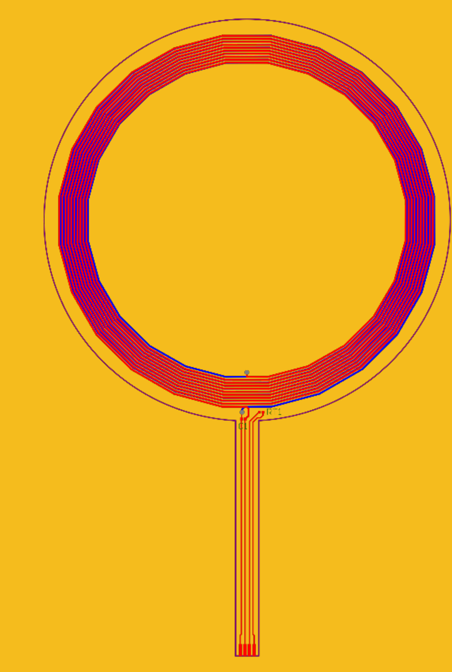

Figure 4: Hollow 2-layer FPC coil with capacitor, NTC Thermistor and edge connector.

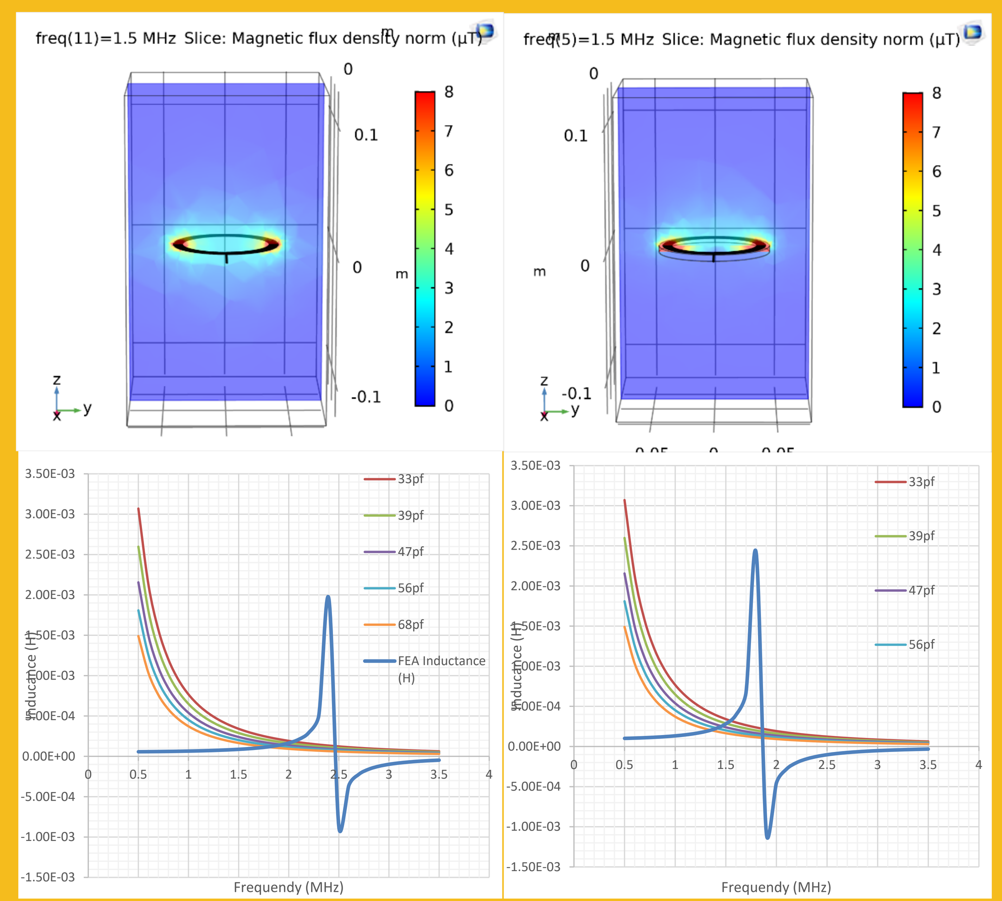

Figure 5: Top Left: FEA without core, Top Right: FEA with core, Bottom Left: Frequency Sweep without core, Bottom Right: Frequency Sweep with core

The base design is then simulated using FEM to validate the use of FEM in next steps. After that, a new FEA model is created with the ferromagnetic core in place. For the new model new results are generated to calculate the inductance against a frequency sweep, super imposed with ideal frequencies of an LC tank for different capacitor values derived from simple mathematical models to find the required configuration of coil and capacitor parameters for a specific operating frequency.

With the specified capacitance and coil parameters fixed, a new FEA model is created with a metal target matching IEC test specifications. With that model a parametric sweep is performed, analyzing the change of inductance and impedance of the coil with change of distance from the metal target. The resulting L and Rp values are then plotted against distance, and compared against the measurement resolution of the Texas Instruments™ LM9100 AFE to find the resolution at different target distance.

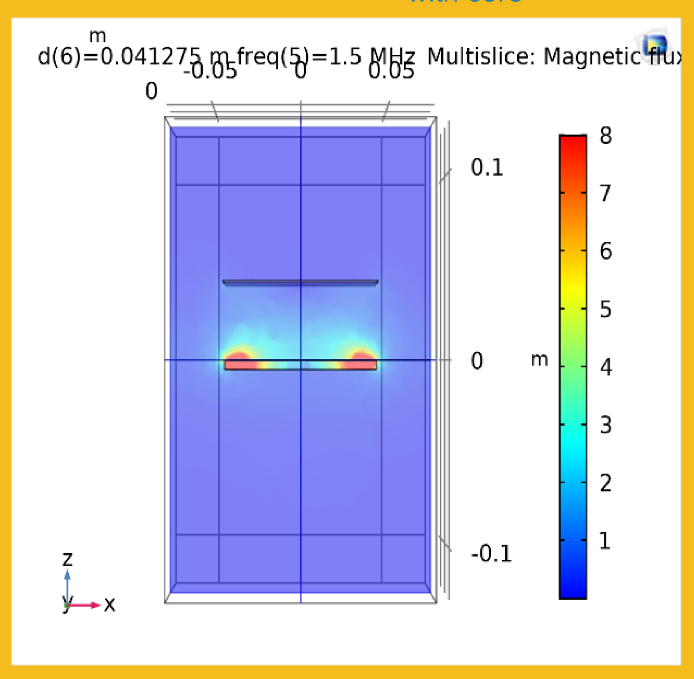

Figure 6: FEA model for parametric sweep with a steel target

RESULTS

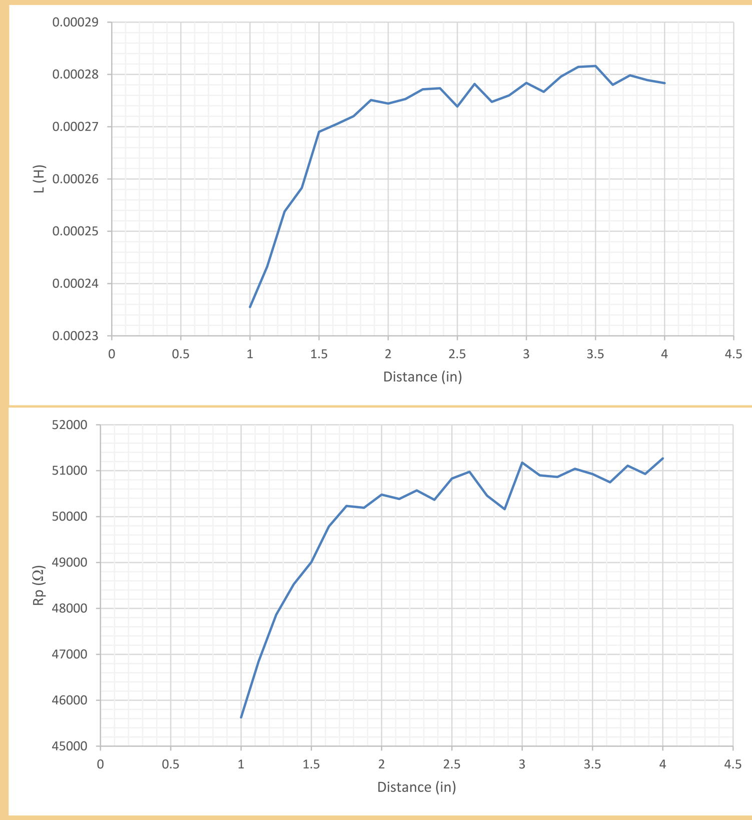

Figure 7: Top: Change of Inductance against target distance, Bottom: Change of parallel losses (Rp) against target distance

Following the Rp determination instructions in LMP9100 Datasheet [11] and from the maximum RP value for our design (51268Ω) we can determine the Rpmax value as 109083Ω and Rpmax value as 27704Ω. Now, with 16-bit resolution, the Rp detection resolution at this setting would be

$$\frac{109083\Omega - 27704\Omega}{2^\wedge 16} = 1.24\Omega$$

At this resolution, if we linearize our data between 3.125" and 3.275" we get the distance detection resolution by

$$\frac{3.375'' - 3.125''}{51041 - 50899} x1.24 = 0.0017''$$

Furthermore, Figure 13 shows the frequency sweep inductance for each distance superimposed on top of each other along with the frequency response of the LC tank inductance with C=39pf to indicate that the frequency also switches with the distance due to the fundamental nature of the LC tank circuit.

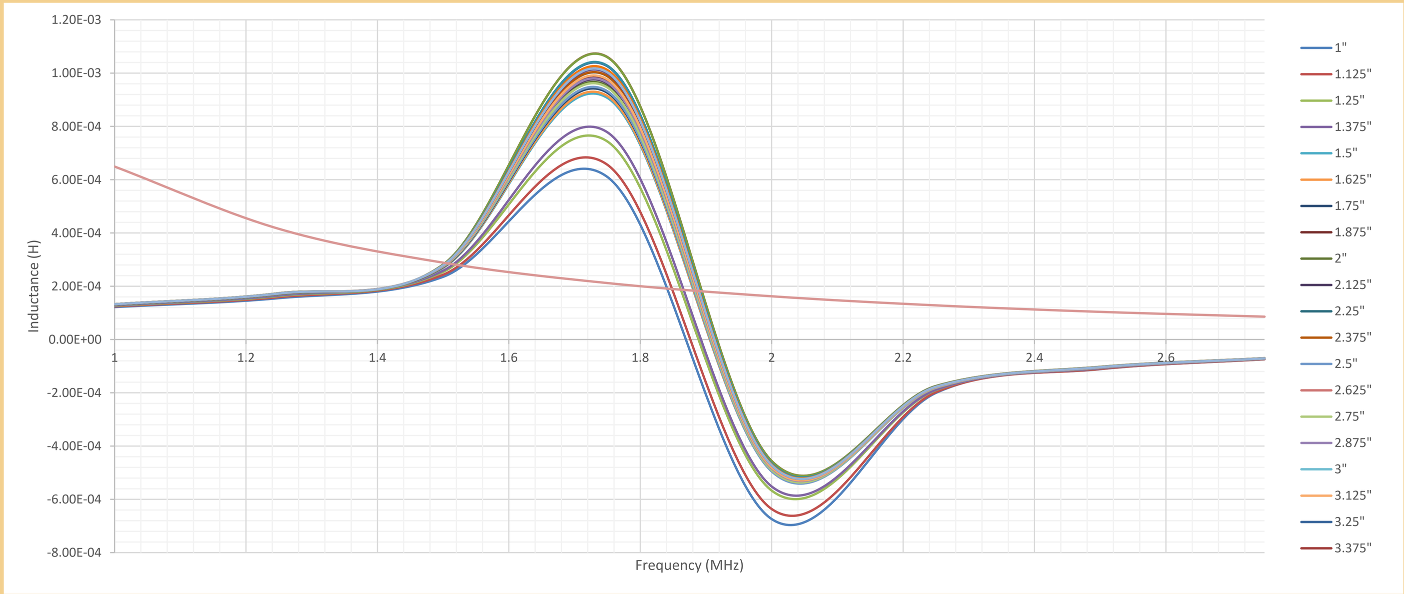

Figure 8: Frequency sweep inductance for each distance superimposed on each other with the LC tank frequency response

CONCLUSION

- From the combination of mathematical model and FEA results it is apparent that this sensor design is viable for up to 0.005" accuracy at a distance equal to the coil diameter.
- But the result shows that the operating frequency of the coil is very close to it's self resonance frequency. Although it could be problematic in sense of stability, further research could be done to utilize this characteristics to boost detection range.
- The above design and analysis was submitted as to the M-WERC/Eaton Tech Challenge 2019, and was chosen as the winning solution, showing potential for industrial application and market viability.

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