Simulation of Coil Separation and Angle Effects on the Mutual Inductance for 13.56 MHz WRAP Sensors

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***Abstract*—Continuous patient monitoring in the normal daily life can be realized with body-worn wireless and fully passive sensors. We have previously developed and optimized a novel Wireless Resistive Analog Passive (WRAP) sensor technology with inductive link between a secondary Printed Spiral Coil (PSC) attached to the body and a wearable scanner with the primary PSC to continuously monitor physiological signal. The flexible and unobtrusive nature of wireless connection between primary and secondary coils causes the distance and the angle between the PSCs to change in real-life operation that can influence the mutual inductance and alter the sensitivity of the whole system. In this paper, we use COMSOL Multiphysics to simulate the effects of varying PSC separation and angle on the mutual inductance for our 13.56 MHz WRAP sensors. We simulate a pair of optimized coil in the cubic infinite boundaries (for magnetic and electric fields) using *mef* (magnetic and electric field) physics in a stationary study. The results show a decrease of 82% in coupling factor with increasing the tilting angle from 0^0 to 60^0. The coupling factor decreases with increasing separation and angle (center-to-edge) in a quadratic function basis.**

I. INTRODUCTION

Monitoring a patient under normal daily life setting has the key role in the early diagnosis, therapy, and health tracking. Wearable sensors are among the best solutions for the continuous monitoring of a subject in the normal life. Removing the meddlesome wires from the wearable sensors not only provides a more natural physical freedom for the subject, but also makes the overall system lighter, less costly, and less susceptible to noise [1,2]. Furthermore, passive sensors make wearable sensors even more practical by eliminating the heavy, costly, and high-maintenance batteries.

We have previously designed a novel technique for chip-less, maintenance-free Wireless Resistive Analog Passive (WRAP) sensor, where inductive coupling between two printed spiral coils (PSC) have been utilized to sense physiological signals [2]. Primary and secondary coil size and characteristics have been optimized using an iterative method and the overall sensitivity has been improved [3]. However, wireless and flexible link between primary and secondary coils leads to the challenge of variation of PSC separation and angle between the primary and secondary coil planes and affects the overall sensitivity. In this paper, we report a simulation study of varying separation and angle between the primary and secondary coil planes using "COMSOL Multiphysics" Finite Element Analysis (FEA) software tool.

II. THEORY

Fig. 1 shows the WRAP sensor system schematic. Mutual inductance, M, is the parameter that represents the primary and secondary coil mutual magnetic effect such that higher M, leads to a more sensitive system. Coupling factor, k, is related to M by (1) where L_1 and L_2 are the self-inductance of coils.

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{1}$$

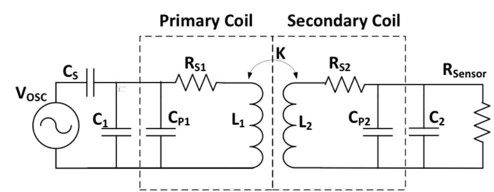

Fig. 1. Wireless Resistive Analog Passive (WRAP) sensor circuit with parasitic components. Variation in the R_{Sensor} is reflected to the Primary coil voltage. C1 and C2 are selected to tune resonance frequency at 13.56 MHz for both sides.

Maximum sensitivity has been achieved by maximizing the power transfer efficiency from primary to secondary that is shown in (2) [3]:

$$\eta = \frac{k^2 Q_1 Q_{2L}}{1+k^2 Q_1 Q_{2L}} \times \frac{Q_2}{Q_2+Q_L} \tag{2}$$

Regarding that all Q's in (2) are independent of k, (2) indicates how k influences the efficiency. In the previous paper [3], k has been assumed as a constant and independent while this paper shows how k changes with coil separation and angle between coil planes. Table I lists the primary and secondary physical specification of a coil pair with optimal performance [3], while Fig. 2 (a) depicts the coil scheme.

Table I. Optimum coil constraints and designed characteristics [3]

Constraints					
Secondary Size d_{O2}	20 [mm]	Maximum Primary size $(d_{O1})_{max}$		40 [mm]	
Minimum Space between Tracks S_{min}	6 [mm]	Minimum Track Width W_{min}		6 [mm]	
Optimum designed Coil					
$\boldsymbol{\eta}$=0.85	d_O [mm]	d_i [mm]	w [mil]	s [mil]	n
Primary	40	7.1	50	20	9
Secondary	20	3.5	31	6	9

III. SIMULATION SETUP

COMSOL Multiphysics 5.1 as an FEA simulation software has been utilized for simulation the coils magnetic field and the effect of separation and angle of coil planes on the mutual inductance. COMSOL simulation requires specification of four aspects: Geometry, Material, Mesh, and Study parameters. Fig. 2 (b) illustrates the 3D input model used for simulation consisting of a primary and a secondary coils.

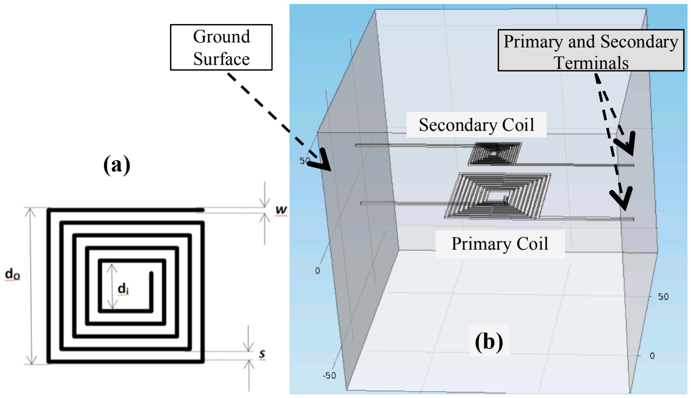

Fig. 2. (a) Coil parameters and configuration. (b) COMSOL 3D model of primary and secondary coils.

The magnetic and electric insulation boundary is constructed from a cube of three times larger than the primary coil size. The electrical characteristics of coils, air, and FR4, the substrate of PCB, are listed in Table II.

Table II. Electrical properties of three materials in the model

	Conductivity	Rel. Permittivity	Rel. Permeability
Copper	59×10^{6} [s/m]	1	1
FR4	30×10^{-18} [s/m]	4.4	1
Air	50×10^{-16} [s/m]	1	1

Fig. 3 shows the two schemes that are used to study the effect of angle between the primary and secondary coils. "Magnetic and Electric Field" (*mef*) with stationary study has been utilized as the physics for simulation.

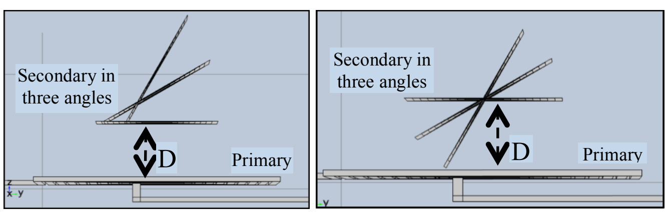

Fig. 3. The 3D model to show three different tilt angles between primary and secondary: 0^0, 30^0 and 60^0. In the left figure, the closest part of the secondary has a constant distance in different angles, while in the right figure, the distance between the centers of primary and secondary coils is constant when the angle is changing.

IV. Simulation Results

Fig. 4 shows the simulation results of coupling factor (k) versus four different (co-axial) separations between primary and secondary planes. Mutual inductance (M) is computed from the surface integral of the vertical component of magnetic flux density that is shown in (3) and (4):

$$\mathrm{M_i} = \frac{\iint \mathrm{mef.Bz}\times\mathrm{dxdy}}{\mathrm{I_1}} \quad (3)$$

$$\mathrm{M} = \sum_{\mathrm{i}=1}^{\mathrm{n_2}} \mathrm{M_i} \quad (4)$$

Where, I_1 is the primary current, $mef.Bz$ is the perpendicular flux density to the secondary coil surface, M_i is the mutual inductance between each turn of secondary and the primary. As it is shown in Fig. 4, k can be estimated by a 2^{nd} order polynomial. Fig. 5 shows the simulation results for two schemes of tilt as given in Fig. 3. If the secondary coil has an angle of α with z-axis, then total the flux is computed by (5):

$$\mathrm{M_i} = \frac{\iint[\mathrm{mef.Bz}\times(\cos\alpha)+|\mathrm{mef.By}|\times(\sin\alpha)]\mathrm{ds}}{\mathrm{I_1}}, \quad \mathrm{M} = \sum_{\mathrm{i}=1}^{\mathrm{n_2}} \mathrm{M_i} \quad (5)$$

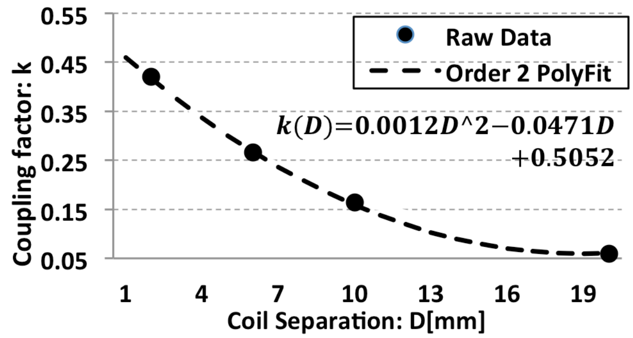

Fig. 4. Coupling factor (k) vs primary-secondary distance. The 2nd order poly-fit trend line is shown.

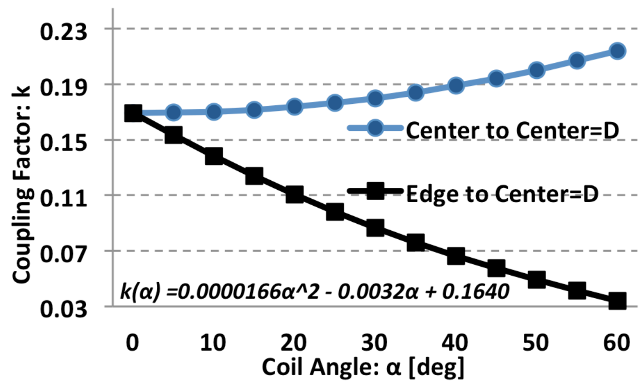

Fig. 5. The effect of angle between primary and secondary coils for D = 10 mm for two schemes as shown in Fig. 3. The 2^{nd} order poly-fit trend line is shown for edge to center scheme.

V. Conclusions

Coil optimization equation depends on coupling factor, which varies with separation and angle between primary and secondary coil planes. Our simulation results of coil magnetic field and mutual inductance shows that the coupling factor decreases with increasing separation distance (co-axial) and angle (with constant center-to-edge distance), and are tightly correlated with empirical quadratic functions.

References

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