Coil Distance and Angle Misalignment Effects on the Mutual Inductance for 13.56 MHz WRAP Sensors

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***Abstract*—In the new era of smart and connected health, new technologies are needed for unobtrusive and seamless monitoring of physiological signals at real life settings. In this grand challenge, we are developing a novel technology called Wireless Resistive Analog Passive (WRAP) sensors. WRAP sensors utilizes printed spiral coil (PSC) inductive link whose sensitivity directly depends on the mutual inductance between primary and secondary coils and it changes due to the physical misalignment. We have previously reported COMSOL simulation results for distance and angular misalignments. In this paper we report experimental results of distance and angular misalignments and compare them to analytical and simulation results for distance. The experimental and analytical results are in good agreement while the simulation results are loosely correlated. For the angular misalignment, the experimental results follow similar trend as simulation results, however analytical results shows disagreement. This work is expected to aid in optimization of PSC for WRAP sensors.**

I. Introduction

Smart and connected health is envisioned to require new ultra-low power technologies for unobtrusive and seamless monitoring of physiological signals. Long term monitoring of these physiological signals in the normal daily life activities increases the chance of subclinical diagnosis of some diseases at home for health and personalized medicine.

We have previously reported **W**ireless **R**esistive **A**nalog **P**assive (WRAP) sensor in which two printed spiral coils (PSC) are employed as the primary and secondary to carry the physiological signals through the inductive coupling [1]. In WARP sensors, obtrusive wires and maintenance-dependent batteries are eliminated to make these wearable sensors more practical. Moreover, maximizing the power transfer efficiency within some constraints maximizes the overall output voltage sensitivity to the physiological signals [2].

However, the unbounded nature of the wireless connection between primary and secondary coils in the WRAP exposes them to the misalignments both in angle and distance that affect the overall sensitivity. Previously, we have reported the simulation results of distance and angular misalignment [3]. In this paper simulation results are compared with new experimental and analytical results.

II. Theory

The WRAP sensor schematic diagram is depicted in Fig. 1.

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It can be shown that the sensitivity of output voltage at primary coil is directly proportion to the Mutual inductance (*MI*) between primary and secondary [2]. The sensitivity is defined as:

$$\text{Sensitivity} = \frac{\Delta V_{OUT}}{\Delta R_{Sensor}} \qquad (1)$$

In an iterative optimization method [1], the primary and secondary PSCs have been optimized for maximum power efficiency, as shown in [2], which also maximizes the sensitivity, within size and fabrication constraints. The constraints and optimized coil pair specifications are depicted in Fig. 2 and Table I. As shown in [4], coil misalignment changes the *MI* that directly affects the sensitivity. There is no analytical *MI* evaluation for rectangular planar coil vs distance and angular misalignments. Hence we are limited to use circular PSC, distance and angle misalignment equations (2) and (3) for analytical results (as given in [4], [5]), while other results are for rectangular PSCs.

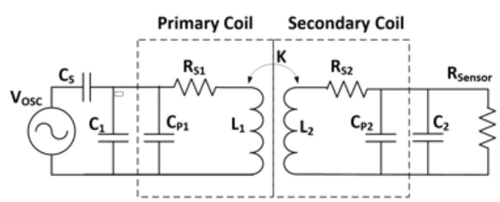


Fig. 1. Wireless Resistive Analog Passive (WRAP) sensor equivalent circuit with parasitic components. R_{Sensor} variation can be probed from the Primary coil voltage (Vout).

$$M = \rho \times \sum_{i=1}^{np} \sum_{j=1}^{ns} M_{ij} \text{ where:}$$

$$M_{ij} = \frac{\mu_0 \pi x_i^2 y_j^2}{2\sqrt{(x_i^2+y_j^2+D^2)^3}}\left(1 + \frac{15}{32}\alpha_{ij}^2 + \frac{315}{1024}\alpha_{ij}^4\right) \qquad (2)$$

Where:

$$x_i = d_{op} - (n_i - 1)(w_p + s_p) - \frac{w_p}{2}$$

$$y_j = d_{os} - (n_j - 1)(w_s + s_s) - \frac{w_s}{2}$$

$$\alpha_{ij} = \frac{2x_i y_j}{x_i^2 + y_j^2 + D^2}$$

$$\rho = (4/\pi)^2 \text{ (for rectangular coil)}$$

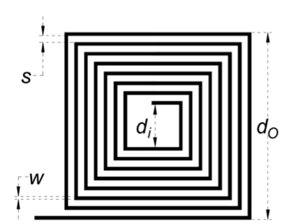


Fig. 2. The PSC layout.

$$M(\theta) = \frac{2\mu}{\pi}\sqrt{d_{OP} d_{OS}} \int_0^{\pi} \frac{\cos\theta}{\sigma\sqrt{V^3}} \times \left(\left(1 - \frac{\sigma^2}{2}\right)K(\sigma) - E(\sigma)\right) d\varphi \qquad (3),$$

where:

$$K(\sigma) = \int_0^{\pi/2} \frac{1}{\sqrt{1-\sigma^2 \sin\gamma^2}} d\gamma,\ E(\sigma) = \int_0^{\pi/2} \sqrt{1-\sigma^2 \sin\gamma^2}\, d\gamma$$

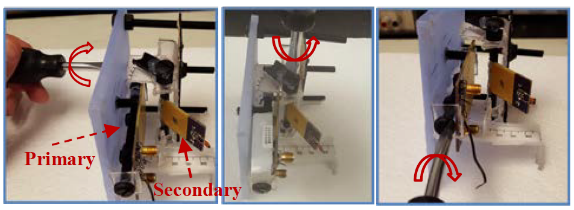
$$\sigma^2 = \frac{4\frac{d_{OS}}{d_{OP}}V}{\left(1+\frac{d_{OS}}{d_{OP}}V\right)^2 + \frac{D}{d_{OP}} - \frac{d_{OS}}{d_{OP}}\cos\varphi \sin\theta},$$

$$V = \sqrt{1-(\sin\theta)^2(\cos\varphi)^2}$$

D, n_P, n_S, and θ are the distance between coils, primary turns, secondary turns, and angular misalignment respectively.

III. Experimental Setup

Fig. 3 shows the experimental setup. The angle and distance between the primary and secondary planes can be changed by two screws in the range of: 0º to 90º and 10 mm to 40 mm, respectively. The secondary coil rotation axis is fixed in a place that rotation does not change the constant distance of two planes. However, to keep the two coil centers aligned, we need third screw to compensate center misalignment due to the rotation.



(a) (b) (c)

Fig. 3. Experimental setup. Two screws make the axial distance (a) and angular misalignment (b) adjustable. The third screw (c) compensates the center misalignment due to rotation of secondary.

IV. Results

To avoid dependency on other measurements, we measure the induced voltage at the output (secondary with no load) and compare the normalized value to simulation and analytic results. Fig. 4 shows the normalized *MI* vs co-axial separations between primary and secondary planes. The results show close agreement of experimental results with analytical results for any distance, however simulation result has loose correlation. Fig. 5 shows the normalized *MI* vs misalignment angle results. In this case, there is some correlation between simulation and experimental results, but the analytical results show discrepancy between experimental and analytical results.

Table I. Coil constraints and optimum specifications

Constraints					
Secondary size (mm): d_{O2}	20	Max. primary size (mm): $(d_{O1})_{max}$			40
Min. track space (mil): S_{min}	6	Min. track width (mil): W_{min}			6
Optimum designed Coil					
η = 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

V. Conclusions

To compensate the misalignment effects on sensitivity and designing the most tolerable coil pair, understanding of the sensitivity changes with respect to misalignments is important. In this paper we attempted to investigate the trend of experimental, simulation (COMSOL), and analytical results.

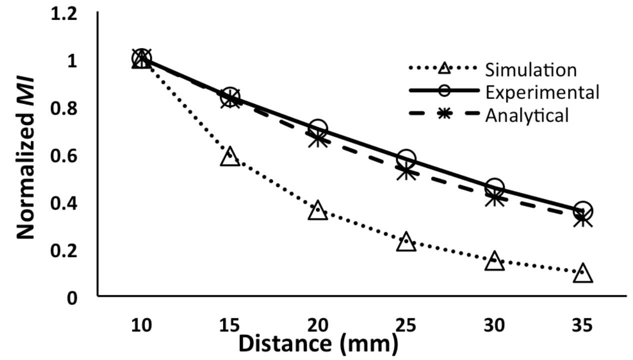


Fig. 4. Normalized *MI* vs distance for analytical, experimental, and simulation results.

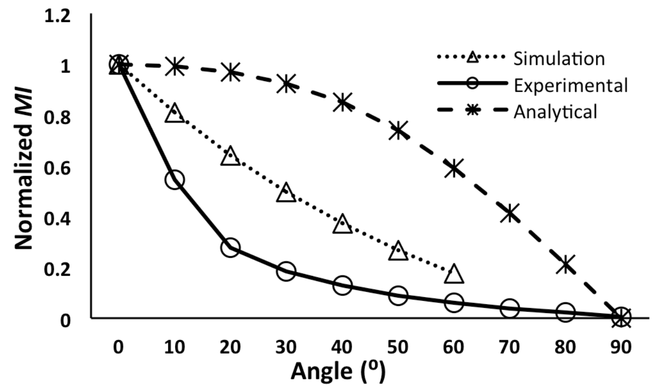


Fig. 5. Normalized *MI* vs distance for analytical, experimental, and simulation results.

The experimental and analytical results are tightly correlated for separation distance, but for angular misalignment, all the three results show disagreement. The analytical angular misalignment equation for circular coils (3) modification for the rectangular coils might lead to a better agreement. This work also reveals that COMSOL simulation settings and boundary conditions might be further improved to account for the mismatch.

References

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