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# Misalignment Tolerable Coil Structure for Biomedical Applications with Wireless Power Transfer

Jeff P. W. Chow, *Student Member, IEEE*, Nan Chen, *Member, IEEE*, Henry S. H. Chung, *Senior Member, IEEE*, and Leanne L. H. Chan, *Member, IEEE*

*Abstract*— **Coil-misalignment is one of the major hurdles for inductively coupled wireless power transfer in applications like retinal prosthesis. Weak magnetic flux linkage due to coil misalignments would significantly impair the power efficiency. A novel receiver configuration with high misalignment tolerance is presented in this paper. The proposed receiver is composed of two receiver coils placed orthogonally, so as to reduce the variation of mutual inductance between transmitting and receiving coils under misalignment conditions. Three different receiver coil structures are analyzed and compared using the same length of wire. Theoretical predictions have been confirmed with measurement results.**

## I. Introduction

Wireless inductive power transfer links has been widely applied in different applications such as cochlear implants [1], retinal prostheses [2], and battery charger [3]. In general, the system is composed of a transmitter, an end-use device, and two sets of loosely-coupled coil with one set in the transmitter, and one set in the end-use device. Electrical energy is transmitted from the transmitter to the device through alternative magnetic fields. Then, under a given operating frequency, maximal power efficiency $\eta$ of coupled coils is dependent on the quality factors of the primary and secondary coils, $Q_1$ and $Q_2$, and the coupling coefficient k between the coils [4].

$$\eta = \frac{k^2 Q_1 Q_2}{[1+\sqrt{1+k^2 Q_1 Q_2}]^2} \quad (1)$$

When coils are operating in high-frequency, frequency-related effects including skin effect and proximity effect will degenerate their quality factors. Coupling coefficient measures the degree of magnetic coupling. Its value $k$ ranges from 0 to 1. When $k = 0$, flux linkage is 0. When $k = 1$, flux linkage is 100%.

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (2)$$

where $M$ is mutual inductance between the coils and it is determined by the coil sizes and geometric spacing. When the coils are coaxially oriented, the coupling is the strongest. However in practice, they are usually misaligned axially, laterally and angularly so that their linkage will be impaired. Taking retinal prostheses as an example, axial and lateral misalignment will occur for displacements of the pair of glasses, whereas angular misalignment will occur for rotations of the eye. A fundamental problem is that the fluctuations in coupling due to misaligned positions of the coils [5] lead to a large variation in power efficiency.

There is a rule of thumb in maximizing misalignment tolerance for disk-shaped primary coil. The primary coil diameter should be larger than that of secondary coil and equal to twice the distance between two coils [6]. However, this design approach has several drawbacks. There is a large portion of magnetic flux generated by an oversized transmitter that is uncoupled to the receiving coil for misaligned conditions and even aligned conditions. The excess flux may cause a problem of electromagnetic radiation.

Research efforts have been put on the coil structures, like multi-layer planar windings [3], [7] and three-dimensional (3-D) windings [8], [9] to enhance magnetic coupling and energy transfer on misaligned coils. The former one is introduced in 2-D applications so it is not designed to tackle angular misalignments. The latter one can only offer *pseudo*-omnidirectional coupling which is an effectively single-coil-to-single-coil coupling. It results in a weak coupling zone around some positions. In order to minimize the impact of misalignments on the power efficiency, a new receiver structure with an additional orthogonal coil on conventional receiving coil is proposed in this paper.

## II. Proposed Misalignment Tolerable Coil Structure

### *A. Mutual Inductance of Proposed Transceiver Coils Under Misalignments*

Given fixed coil configurations, the power efficiency increases with the mutual inductance $M$ between the transmitting coil and the receiving coil. The mutual inductance is defined as the number of flux linkage with the secondary coil due to unit current in primary coil and it can be determined by Neumann formula [10]. Empirically, it is advantageous to align the receiving coil orthogonally to the magnetic flux generated by the transmitting coil in order to achieve the maximum flux linkage between the coils. However, in many practical applications, like implantable devices, the two coils position between each other is not fixed, they could have combined axial, lateral and angular misalignment. The resulting mutual inductance between the coils will be affected considerably. In this paper, lateral and

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angular misalignments between square shaped coils will be studied. Figure 1 illustrates the two square coils under misalignments, in which Δ represents the displacements from their centers and $\theta$ represents the angle between the planes of the two coils. The mutual inductance and energy efficiency of this coil configuration will decrease quickly toward zero when the misalignment increases.

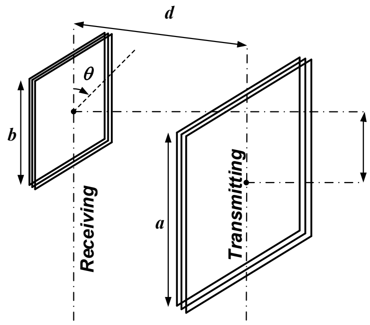

Figure 1. Basic structure of the square induction coils.

To reduce the variation of mutual inductance in the presence of misalignment, a receiving coil composed of parallel windings and orthogonal windings is proposed and is shown in Figure 2. These two coils have the same dimensions and total number of turns. Symbol $M_p$ represents the mutual inductance between transmitting windings and receiving parallel windings. Symbol $M_o$ is defined as the mutual inductance between transmitting windings and receiving orthogonal windings.

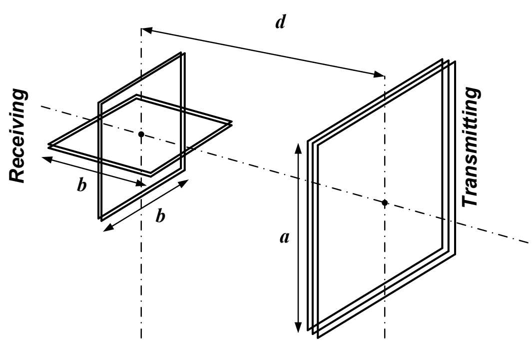

Figure 2. Structure of the square induction coils with orthogonal windings.

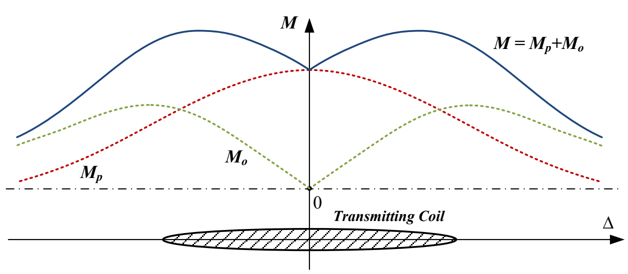

Figure 3. Variation of mutual inductance under lateral misalignments

In order to assure that the overall mutual inductance $M$ is always the absolute sum of $M_p$ and $M_o$, the circuit connection between the parallel windings and orthogonal windings will be interchanged according to the misalignment conditions. Thus $M_o$ would be positive for all misalignment conditions. Figure 3 illustrates the variation of $M_p$, $M_o$ and $M$ under the interchanged series connection of the two receiving windings.

When the coils are aligned perfectly, $M_p$ and $M_o$ are maximized and minimized respectively. While the misalignment increases, $M_p$ drops but $M_o$ rises up and then declines slowly. Therefore, the overall transmitter-receiver mutual inductance becomes more even and more tolerable for misalignments.

### *B. Equivalent Circuit*

The inductive power transfer link can be modeled as a loosely coupled transformer [11]. The equivalent circuit is shown in Figure 4. There are two possible coil connections for the proposed receiving coil. The first one is to connect the parallel windings in series with the orthogonal windings, i.e., series coil connection (SCC). The second one is to connect them in parallel, i.e., parallel coil connection (PCC). The parallel coil and orthogonal coil have the same structure and the position between them is fixed orthogonally. Hence, the mutual inductance between them is zero, their equivalent inductance and resistance are defined as $L$ and $r$ . $L_{tr}$ and $r_{tr}$ are used for the transmitter coil. Table I provides the transformer model parameters of the proposed coil structure in series and parallel connections.

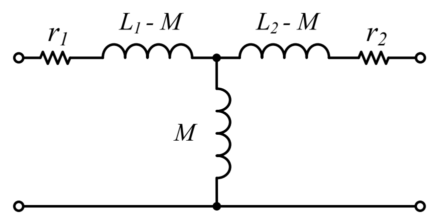

Figure 4. Equivalent circuit of a loosely coupled transformer.( $L_1$ and $r_1$ are defined as self-inductance and the total parasitic resistance of primary coil. $L_2$ and $r_2$ are used for secondary coil.)

TABLE I. THE TRANSFORMER MODEL PARAMETERS WITH DIFFERENT CONNECTIONS

| Series coil connection (SCC) | Parallel coil connection (PCC) |
|---|---|
| $M = M_p + M_o$ | $M = \frac{M_p + M_o}{2}$ |
| $L_1 = L_{tr}$ | ** $L_1 \approx L_{tr}$ |
| $r_1 = r_{tr}$ | ** $r_1 \approx r_{tr}$ |
| $L_2 = 2L$ | $L_2 = \frac{L}{2}$ |
| $r_2 = 2r$ | $r_2 = \frac{r}{2}$ |

** The approximations can be applied since $L >> \left| M_p - M_o \right|$.

### *C. Power Transfer Efficiency*

To improve the efficiency of the power transfer link, a resonant capacitor, $C_r$, is commonly connected to the receiving coil. The capacitance is designed to resonate with the secondary winding inductance on operating frequency [12]. $C_r$ is either in the form of series [13] and parallel connections [14], as shown in Figure 5 and 6, respectively.

$$C_r = \frac{1}{\omega^2 L_2} \tag{3}$$

In the following analysis, the load is represented by a resistor $R_L$. The link efficiency $\eta$ is defined as follows,

$$\eta = \frac{P_L}{P_{in}} \tag{4}$$

where $P_{in}$ and $P_L$ are the input power on the transmitting coil and output power on the load resistor.

*With Series Resonant-Capacitor (SRC)*

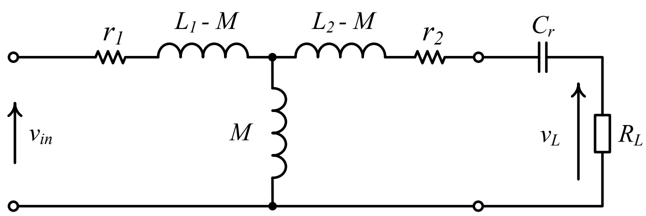


Figure 5. Equivalent circuit of loosely coupled transformer with series resonant-capacitor.( $v_L$ is the voltage across the load resistance and $v_{in}$ is the voltage across the transmitting coil.)

The power efficiency can be shown to be

$$\eta_{sc} = \frac{(\omega M)^2 R_L}{(R_L + r_2)^2 r_1 + (\omega L_2 - \frac{1}{\omega C_r})^2 r_1 + (\omega M)^2 (R_L + r_2)} \tag{5}$$

When the coil electrical characteristic and excitation frequency are designed, optimal load resistance for maximum power efficiency can be derived as

$$R_{L,sc} = \sqrt{r_2^2 + (\omega M)^2 \frac{r_2}{r_1}} \tag{6}$$

*With Parallel Resonant- Capacitor (PRC)*

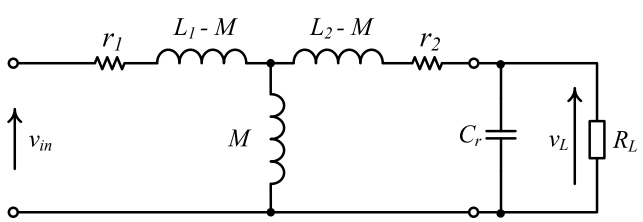


Figure 6. Equivalent circuit of loosely coupled transformer with parallel resonant-capacitor.

The power efficiency can be shown to be

$$\eta_{pc} = \frac{\dfrac{(\omega M)^2 R_L}{(\omega C_r R_L)^2 + 1}}{\left[ \begin{array}{l} r_1 \left( \dfrac{R_L}{(\omega C_r R_L)^2 + 1} + r_2 \right)^2 + \dfrac{(\omega M)^2 R_L}{(\omega C_r R_L)^2 + 1} \\ + \left( L_2 - \dfrac{C_r R_L^2}{(\omega C_r R_L)^2 + 1} \right)^2 \omega^2 r_1 + (\omega M)^2 r_2 \end{array} \right]} \tag{7}$$

Optimal load resistance can be derived as

$$R_{L,pc} = \omega L_2 \sqrt{\frac{r_1 r_2^2 + r_1 (\omega L_2)^2 + r_2 (\omega M)^2}{r_1 r_2^2 + r_2 (\omega M)^2}} \tag{8}$$

According to (6) and (8), the load with parallel capacitor is relatively appropriate for larger resistive load application.

## III. VERIFICATION

The geometric parameters of two transceiver coil setups shown in Figure 1 and 2 are listed in Table II. An experimental prototype (figure not shown) consisting of these two setups are built for experimental verification. By theoretical calculation and experimental measurements, the percentage variation in $M$ of the cross receiving coil in both SCC and PCC are the same. Thus, only the results of SCC are given in Figure 7. Figure 7(a) gives the measured and calculated percentage variation of $M$ with $\theta = 0°$ against the lateral misalignment. Figure 7(b) shows the percentage variation of $M$ with $\Delta = 0\,cm$ against the angular misalignment. The mutual inductance of the proposed structure is reduced to 60 %, when two coils are displaced laterally by 75% with respect to the transmitting coil diameter or displaced angularly by around 90 ° . Compared to traditional single parallel receiver design, the new design can afford a wider misalignment range for the given normalized $M$ variation band.

TABLE II. THE GEOMETRIC PARAMETERS OF THE SQUARE INDUCTION COILS.

| a/cm | b/cm | d/cm | Number of turns | | |
|---|---|---|---|---|---|
| | | | **Transmitting** | **Receiving (Parallel)** | **Receiving (Orthogonal)** |
| 4.3 | 2.2 | 3 | 20 | 12 | 0 |
| 4.3 | 2.2 | 3 | 20 | 6 | 6 |

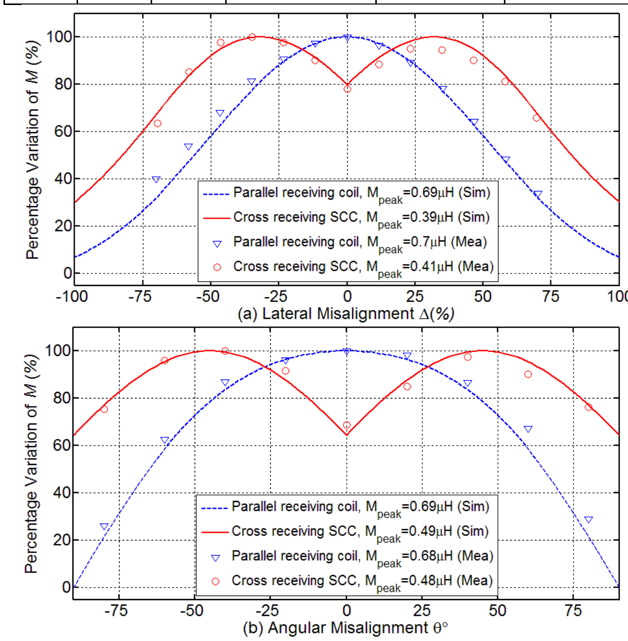


Figure 7. Variation of $M$ of the single parallel receiver coil structure and the proposed coil structure under (a) lateral and (b) angular misalignments.

To reduce the coil resistance, litz wire is used in winding coils. The equivalent inductance and resistance of transmitting coil in 2.2MHz excitation are 39.06 μH and 10.31 Ω respectively. The electrical parameters of three different receiving coils are listed in Table III. The change in percentage of $\eta_{sc}$ and $\eta_{pc}$ with properly chosen $C_r$ and $R_L$ are similar and hence, only the results of $\eta_{pc}$ are presented here. Figure 8 illustrates the normalized efficiency under both misalignments and the load resistance is 2185 Ω .

TABLE III. THREE SETS OF COIL PARAMETERS USED IN BELOW ANALYSIS.

| | $L_2/\mu H$ | $r_2/\Omega$ | $C_r/pF$ |
|---|---|---|---|
| **Single parallel receiving coil** | 7.29 | 2.64 | 706 |
| **Cross receiving coil in series** | 3.84 | 1.57 | 1337 |
| **Cross receiving coil in parallel** | 1.07 | 0.56 | 4858 |

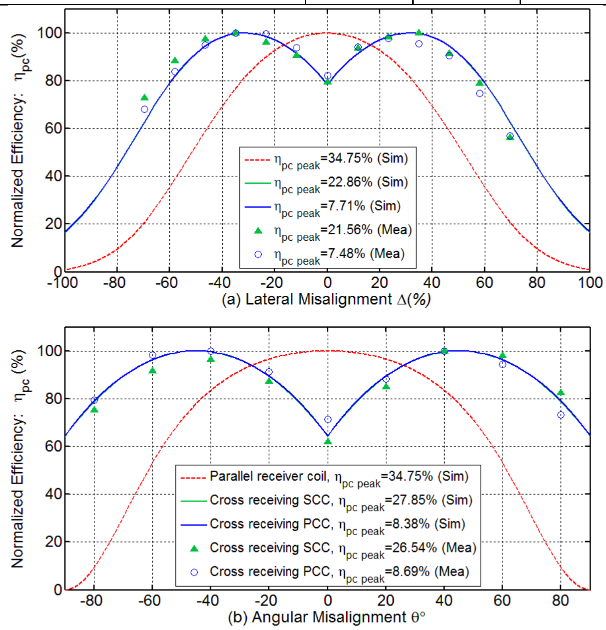


Figure 8. Comparisons of normalized efficiency $\eta_{pc}$ between single parallel receiving and cross receiving coil structures under (a) lateral and (b) angular misalignments.

Structures SCC and PCC have similar normalized efficiency curves, due to the same mutual inductance variation. Given the maximum efficiency variation is within 40% of respective peak efficiency, it can be seen from Figure 8 that the proposed receiving coils can allow 70% absolute lateral misalignment and 90° absolute angular misalignment, while for single parallel receiving coil setup, the allowed misalignment range is around 45% and 60° respectively only. What is more, it is important to note that under angular misalignment *M* and normalized efficiency with traditional design can fall to zero, but the proposed receiver can always maintain above 60%. By comparing the results of efficiency with three different receiving coil structures, it is obvious that the additional orthogonal configuration offers a relatively constant normalized efficiency under a wide misalignment condition. Nevertheless, the trade-off for the new design is the increased coil size. Under the same length of wire used, the maximum power efficiency is generally lower than that of the single parallel structure. Some experimental data is shown in Table IV. To achieve a higher efficiency practically, the quality factors can be increased by further reducing the winding resistance, which can reduced by optimizing the materials used, for the wires, the number of strands, etc.

## IV. CONCLUSION

By introducing orthogonal windings on the receiving coil, less variation of power efficiency against misalignments is achieved and hence, allowing a larger misalignment tolerant for inductive coupling coils. The trade-off of proposed structure is the peak coupling coefficient will be lower, which in turn affect power efficiency. But on the other hand, power transfer efficiency also depends on the coil quality factors, so the efficiency profiles can be further improved by reducing the coil ac resistance. In future study, optimization on the proposed coil structure design will be further investigated.

TABLE IV. THE EXPERMENTAL RESULTS OF $M$ AND $\eta_{PC}$ UNDER LATERAL MISALIGNMENTS

| $\Delta$ / cm | Single Parallel receiving coil | | Cross receiving coil in series | | Cross receiving coil in parallel | |
|---|---|---|---|---|---|---|
| | $M/\mu H$ | $\eta_{pc}$ / % | $M/\mu H$ | $\eta_{pc}$ / % | $M/\mu H$ | $\eta_{pc}$ / % |
| 3.0 | 0.24 | 9.24 | 0.27 | 12.11 | 0.12 | 4.26 |
| 2.5 | 0.34 | 15.23 | 0.33 | 17.02 | 0.15 | 5.59 |
| 2.0 | 0.45 | 21.98 | 0.37 | 19.71 | 0.17 | 6.76 |
| 1.5 | 0.55 | 27.28 | 0.39 | 21.56 | 0.19 | 7.14 |
| 1.0 | 0.63 | 31.28 | 0.39 | 21.18 | 0.19 | 7.31 |
| 0.5 | 0.68 | 33.33 | 0.36 | 20.16 | 0.17 | 7.04 |
| 0.0 | 0.70 | 33.06 | 0.32 | 17.13 | 0.16 | 6.14 |
| -0.5 | 0.68 | 32.26 | 0.37 | 19.48 | 0.18 | 7.02 |
| -1.0 | 0.64 | 29.73 | 0.40 | 20.69 | 0.19 | 7.45 |
| -1.5 | 0.57 | 26.00 | 0.41 | 21.51 | 0.19 | 7.48 |
| -2.0 | 0.48 | 21.05 | 0.40 | 21.00 | 0.19 | 7.09 |
| -2.5 | 0.38 | 15.55 | 0.35 | 19.02 | 0.17 | 6.27 |
| -3.0 | 0.28 | 8.93 | 0.26 | 15.67 | 0.14 | 5.08 |

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