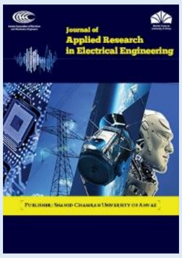
Shahid Chamran University of Ahvaz

Iranian Association of Electrical and Electronics Engineers

Journal of Applied Research in Electrical Engineering

E-ISSN: 2783-2864
P-ISSN: 2717-414X
Homepage: https://jaree.scu.ac.ir/



Research Article

Investigating the Effect of Geometric Design Parameters on the Mutual Inductance Between Two Similar Planar Spiral Coils With Inner and Outer Diameter Limits

Ata Ollah Mirzaei [1], Amir Musa Abazari [1,*], and Hadi Tavakkoli [2]

[1] *Department of Mechanical Engineering, Faculty of Engineering, Urmia University, Urmia 5756151818, Iran*

[2] *Department of Mechanical and Aerospace Engineering, Hong Kong University of Science and Technology, Hong Kong*

[*] *Corresponding Author: am.abazari@urmia.ac.ir*

Abstract: Nowadays, planar spiral coils are widely used in different applications. Mutual inductance of two adjacent coils, is one of the critical operating principles in near-field wireless power and data transmission systems, significantly impacting their performance. Hence, in this study, the mutual inductance between two similar concentric planar spiral coils is investigated. The effect of main parameters, including the track width, w, and the space between two consecutive turns, s, with a fixed inner and outer diameter of the coils are investigated. The Taguchi method using the L16 array in Minitab environment is used to optimize design parameters. The samples of applied Taguchi, are modeled and simulated via ANSYS Maxwell. The results show that the mutual inductance increases by reducing the two investigated parameters. Based on the Taguchi analysis, it is revealed that the effect of the response for both of the investigated parameters is very close. By applying the main effect analysis the obtained results are verified. This interesting result is important in the design of planar spiral coils while we have fabrication limitations in a real sensor design realization.

Keywords: Mutual inductance, planar coil, 3D modeling.

Article history
Received 26 March 2022; Revised 06 November 2022; Accepted 06 December 2022; Published online 29 March 2023.

How to cite this article
A. O. Mirzaei, A. M. Abazari, and H. Tavakkoli, "Investigating the effect of geometric design parameters on the mutual inductance between two similar planar spiral coils with inner and outer diameter limits," *J. Appl. Res. Electr. Eng.*, vol. 2, no. 1, pp. 70-74, 2023. DOI: 10.22055/jaree.2022.40372.1053

1. Introduction

Planar coils are widely utilized in diverse applications, from blood pressure measurement to fabrication of electronic cards. These coils are considered as a proper wireless connection choice, especially in a limited space [1]. Calculation of inductance and resistance for planar coils is critical because of their vital and direct role in the performance of coils. They are called planar or flat coils due to placement of the coil components almost on a plane. This is a huge advantage comparing with solenoid coils; because they occupy less space than solenoid coils; so, they are suitable for applications with size constraints such as Micro-electromechanical systems (MEMS) [2] or implantable medical components (e.g., heart pumps). Planar coils can be built on a rigid or non-rigid substrate; it means that they can be integrated on the Printed Circuit Boards (PCBs) as well as flexible substrates. Planar coils can be produced in the batch production systems, which leads to a cost-effective manufacturing process. According to these features, planar coils have different applications such as remote health monitoring, wireless power transmission, induction heating, and radiofrequency detection [3]. Mutual inductance of two adjacent coils, is one of the critical operating principles in near field wireless power and data transmission systems, significantly impacting their performance. Hence, in this study, the mutual inductance between two similar concentric planar spiral coils are investigated. In particular, two different analytical methods exist to compute the mutual inductance between two coils, including loop inductance procedure and partial inductance procedure. While the loop inductance procedure calculates the inductance considering the whole structure, the partial inductance procedure deals with each part of the coil. One of these methods can be employed as an optimal method to solve the problem based on the geometric features of the structure. For example, in structures with unparalleled planar coils, the loop method makes the situation complicated. Grover [4] presented a model to calculate the mutual inductance between two wires located in the desired position in the space; this method calculates the mutual inductance between the studied two wires well. Based on this model, Cheng and Shu [5] provided a relationship for computing the mutual inductance between two square-shaped coaxial loops using the partial inductance procedure; although the method can calculate the mutual inductance between the square-shaped loops, but it is not suitable for non-square and polygon loops. Greenhouse [6], also tried to use the partial method to calculate the inductance of a square-shaped planar spiral coil. Abbaspour et al. [7] used the partial inductance to obtain the mutual inductance between two square-shaped coils, which was limited by the shape and location of the coils. Tavakkoli et al. [8] suggested a novel model based on the partial inductance procedure that calculates the mutual inductance between two parallel coaxial planar spiral coils with arbitrary number of sides; in their study, they have compared the results of their method with practical experiments and computer simulations and show that their method works well in comparison to the others' result. However, this method requires two coaxial and paralleled coils, limiting its application. Ji et al. [9] used relationship to calculate the mutual inductance between the circular and square coils using the circular matrix. Inferring from Newman's relationship, they proposed a method to calculate the mutual inductance between two coils in the arbitrary states. This method can be considered as an essential step in the field due to removing spatial constraints from the computation. However, it can calculate the mutual inductance between two coils in the arbitrary states but it is geometrically limited to circular and square coils. Due to the importance of the planar spiral coils, there are a lot of studies around this subject. The design parameters of the planar spiral coils and their optimization are important and at the same time, interesting topic in this field. The design parameters directly affect the different properties of the coils. For example, Chen et al. [10] investigated the effect of design parameters on the resonant frequency in the double layer printed spiral coils to transfer the wireless power. In the previous studies the direct impact of geometrical parameters, such as the track thickness, track width or space between two consecutive turns of the coil, on the mutual inductance is not studied. Hence, in this paper, we investigate the effect of mentioned parameters on the mutual inductance between two similar planar spiral coils with internal and external diameter limits. Considering the whole permutations for all of design parameters, can be time-consuming and sometimes it is impossible. Therefore, in order to investigate the effect of geometric parameters on mutual inductance, we used the Taguchi design method which reduces the number of the cases and can achieve a desired result in an optimal state. The Taguchi method optimizes design parameters to minimize variation before optimizing design to hit mean target values for output parameters [11]. The extracted cases of Taguchi are modelled and simulated via ANSYS Maxwell to get the simulation results and then, the simulation results are analyzed using the Taguchi analysis method. The main effect analysis is used to verify the final results.

2. Materials and Methods

2.1. Design of Simulations

As it stated, Taguchi method is a powerful tool for the design of high quality systems. It is a simple, efficient and systematic approach to optimize designs for performance, quality, and cost. The methodology is valuable when the design parameters are qualitative and discrete. Parameter design via Taguchi can optimize the performance characteristics through the setting of design parameters and reduce the sensitivity of the system performance to sources of variation [11]. Fewer experiments/simulations means less time and cost. Taguchi provides an orthogonal array of variables and levels for experiments/simulations. Taguchi method proposes a minimum number of necessary experiments/simulations to reach a proper conclusion [12]. So, due to the large number of the cases for an all-inclusive analysis of geometric parameters, we tried to use the Taguchi method to design our cases for an optimal simulation process; and here, the impact of the width of the track, *w*, and space between two consecutive turns of the coil, *s*, on the mutual inductance between two concentric similar planar circular coils considering a limit for inner diameter, d_i, and also a limit for outer diameter, d_o, is investigated (see Fig. 1).

According to Table 1, two parameters, i.e., *w* and *s* are introduced to Minitab software as factors in four levels. The designs are simulated using the ANSYS Maxwell software according the Taguchi L16 orthogonal array which is applied in Minitab software. Table 2 presents the configuration of the designs.

2.2. Finite Element Analysis (FEA)

FEA methods are widely used in scientific and industrial studies. In the field of electromagnetics, also, simulation software are widely developed. ANSYS Maxwell software is one of them which is widely used in the study of various problems in the field of electromagnetics. In particular, recently, the use of this software for studying the mutual inductance in planar inductors attracted a great interest. Due to its capabilities and ease of use, in this article, ANSYS Maxwell software is used to simulate and calculate the mutual inductance between two planar coils.

The samples of Taguchi's result, are modelled and simulated via ANSYS Maxwell. The coils are designed in the circular shape with a rectangular cross-section; d_i, d_o, track thickness, and vertical space between two fixed coils are considered 5, 15, 0.02, and 10 mm, respectively. In all of the models, coils' material are considered to be "copper" and the surrounding environment is assumed to be "air". Fig. 2 shows a sample of two planar spiral coils in ANSYS Maxwell software. It is noted that in the modelling of samples and

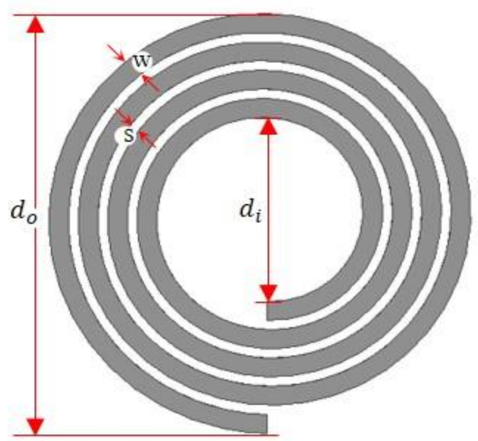


Fig. 1: The used parameters in the modeling.

Table 1: Variables and levels.

Variables	Levels			
	1	2	3	4
w [mm]	2	2.5	3	3.5
s [mm]	0.5	1	1.5	2

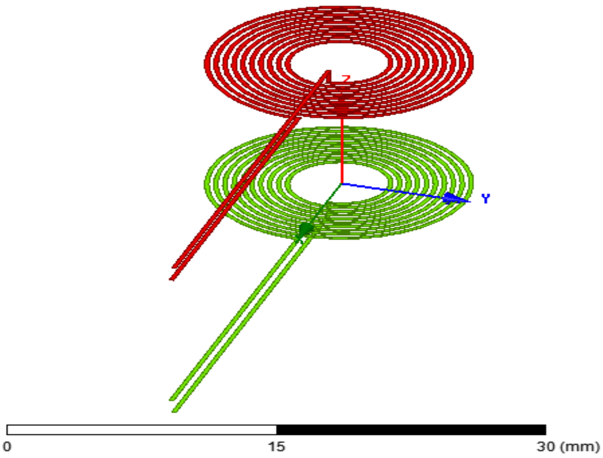


Fig. 2: A sample of two concentric planar spiral circular coils in ANSYS Maxwell software.

Table 2: The configuration of simulations using Taguchi's L16 orthogonal array and the obtained results.

sample number	*w*	*s*	Mutual Inductance [nH]
1	1	1	73.87
2	1	2	41.46
3	1	3	18.83
4	1	4	12.41
5	2	1	41.52
6	2	2	19.90
7	2	3	12.89
8	2	4	8.74
9	3	1	19.13
10	3	2	13.21
11	3	3	8.27
12	3	4	6.32
13	4	1	12.61
14	4	2	8.79
15	4	3	6.43
16	4	4	5.49

based on (1), the number of coil turns is a function of *w* and *s*, while internal and external diameters of planar coils are considered the same in all samples.

$$N = \frac{d_o - d_i}{2(w + s)} \tag{1}$$

where N, d_i, d_o, s and w are the number of turns, inner diameter, outer diameter, space between two consecutive turns, and track width of the coil, respectively.

3. Results

The results for the effect of the track width and spacing between two consecutive turns on the mutual inductance between two concentric planar spiral circular coils by applying a limit on inner and outer diameters is presented here. The results of the simulation for proposed Taguchi's samples are reported in Table 2 as well as in Fig. 3.

Fig. 3 illustrates the variation of the mutual inductance value between two similar concentric planar spiral circular coils at the vertical distance of 10 mm from each other, the inner diameter of 5 mm, outer diameter of 15 mm, and track thickness of 0.02 mm with respect to the variation of space between two consecutive turns and track width of the coil. According to this graph, one can easily observe that the decrease of studied parameters, i.e. *w* and *s*, leads to an increase in mutual inductance value. Here, it should be notified that reducing *w* and *s* will increase the mutual inductance, but *w* and *s* reduction will increase DC resistance and coupling capacitance, respectively.

Fig. 4 shows the magnetic field density on the zy plane (Fig. 2) for sample 1 at Table 2.

Finally, to investigate and analyze the results of simulations, the mutual inductance values are entered into Minitab Software, and then Taguchi design analysis is performed on the data. The results of this analysis are presented in Table 3 and Fig. 5. Table 3 shows the signal-to-noise ratio for each factor at different levels. This ratio expresses the scattering around the specific value. The more the ratio is, the less the scattering is. So, the impact of the scattering variable will be more important.

In Table 3, delta which shows the difference between the highest and lowest mean response values for each factor, represents the relative impact of each factor on the response. The more the delta for each factor is, the more the impact on the response is. Regarding the delta value, the effective factors can be ranked [13]. According to the results in Table 3 and the delta values, which are 28.31and 28.54 for *w* and *s*, respectively, it can be concluded that the variation impact of both parameters on the mutual inductance between two planar coils is almost the same.

Fig. 5 shows diagram graph which is related to the analysis of the main effect. It represents the impact of variables on the output values. According to section w, at the left side of Fig. 5, one can see that the smaller the track width is, the more the mutual inductance is. Also, the *s* section, at the right side, indicates that the smaller the space between two consecutive turns is, a higher value for the mutual inductance can be obtained. Therefore, the main effect analysis verifies the results of previous analyses.

4. Conclusion

In this article, the impact of track width, *w*, and spacing between two consecutive turns of the coils, *s*, on the mutual inductance between two concentric planar spiral circular coils was investigated for a fixed inner and outer diameters. For this purpose Taguchi method was used to design an optimal simulation table. Then, ANSYS Maxwell software was used to calculate the mutual inductance between two coils. The mutual inductance obtained from simulation results, are analyzed by Taguchi concepts and the main effect analysis is also performed to verify the results. The obtained results and performed analyses shows that the reduction of *w* and *s* lead to an increase in mutual inductance. Based on the results, it is shown that the effect of both of the investigated parameters,

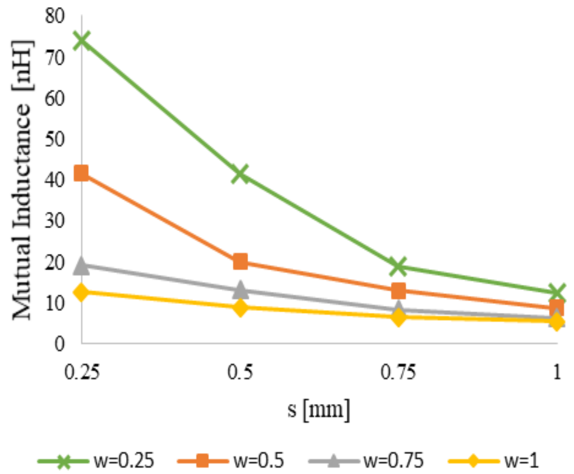


Fig. 3: The variation of mutual inductance value with respect to the variation of the space between two consecutive turns, *s*, and track width, *w*, of the coils.

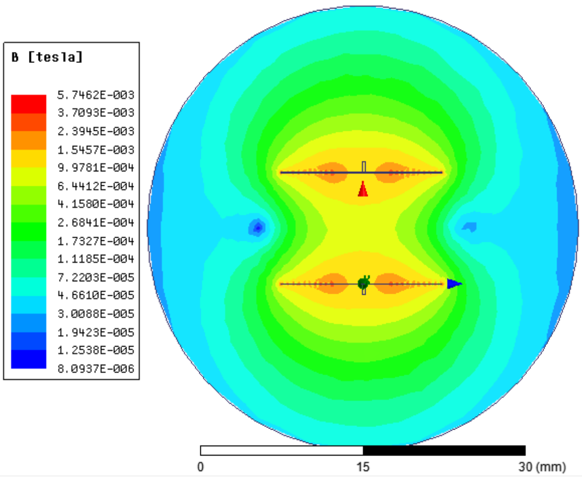


Fig. 4: The magnetic field density on the zy plane (Fig. 2) for sample 1 at Table 2.

Table 3: Signal to noise ratio (larger is better).

Level	*w*	*s*
1	36.64	36.78
2	20.76	20.84
3	11.83	11.61
4	8.33	8.24
Delta	28.31	28.54
Rank	2	1

i.e. *w* and *s*, is very close to each other. This compelling result is important in design of planar spiral coils where fabrication issues can be a challenge in real applications. Finally, we declare that although, reducing *w* and *s* will increase the mutual inductance, it will increase DC resistance and coupling capacitance. The important point is that the mutual inductance is not the only effective factor in the systems associated with planar coils; and the coil resistance and coupling capacitance must also be considered in the design of

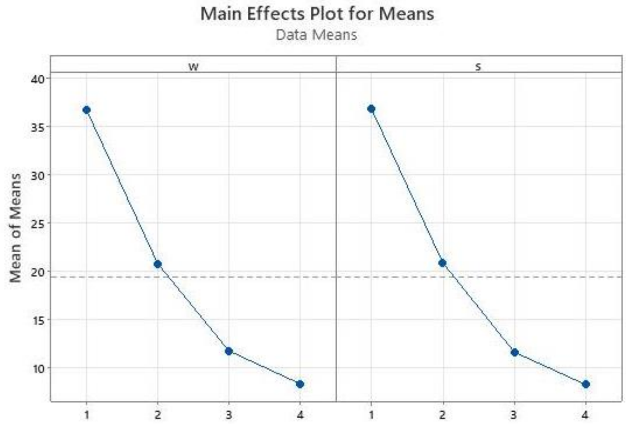


Fig. 5: The result obtained from the main effect analysis.

such a system. So, these side effects must be considered depending on any specific application which can be studied in the future works.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ata Ollah Mirzaei: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing - original draft. **Amir Musa Abazari:** Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing. **Hadi Tavakkoli:** Conceptualization, Investigation, Supervision,

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

REFERENCES

[1] L. Qian, M. Chen, K. Cui, G. Shi, J. Wang, and Y. Xia, "Modeling of mutual inductance between two misalignment planar coils in wireless power transfer," *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 8, pp. 814-817, 2020.

[2] C. H. Ahn, and M. G. Allen, "Micromachined planar inductors on silicon wafers for MEMS applications," *IEEE Transactions on Industrial Electronics*, vol. 45, no. 6, pp. 866-876, 1998.

[3] G. M. Moreton, "The design and development of a planar coil sensor for angular displacements," Ph.D. Thesis, Cardiff University, 2018.

[4] F. W. Grover, *Inductance calculations: working formulas and tables*. Courier Corporation, 2004.

[5] Y. Cheng, and Y. Shu, "A new analytical calculation of the mutual inductance of the coaxial spiral rectangular coils," *IEEE Transactions on Magnetics*, vol. 50, no. 4, pp. 1-6, 2013.

[6] H. Greenhouse, "Design of planar rectangular microelectronic inductors," *IEEE Transactions on parts, hybrids, and packaging*, vol. 10, no. 2, pp. 101-109, 1974.

[7] E. Abbaspour-Sani, R. -S. Huang, and C. Y. Kwok, "A linear electromagnetic accelerometer," *Sensors and Actuators A: Physical*, vol. 44, no. 2, pp. 103-109, 1994.

[8] H. Tavakkoli, E. Abbaspour-Sani, A. Khalilzadegan, A.-M. Abazari, and G. Rezazadeh, "Mutual inductance calculation between two coaxial planar spiral coils with an arbitrary number of sides," *Microelectronics Journal*, vol. 85, pp. 98-108, 2019.

[9] Y. Ji, H. Wang, J. Lin, S. Guan, X. Feng, and S. Li, "The mutual inductance calculation between circular and quadrilateral coils at arbitrary attitudes using a rotation matrix for airborne transient electromagnetic systems," *Journal of Applied Geophysics*, vol. 111, pp. 211-219, 2014.

[10] K. Chen, and Z. Zhao, "Analysis of the double-layer printed spiral coil for wireless power transfer," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 2, pp. 114-121, 2013.

[11] W. P. Yang, and Y. Tarng, "Design optimization of cutting parameters for turning operations based on the Taguchi method," *Journal of Materials Processing Technology*, vol. 84, no. 1-3, pp. 122-129, 1998.

[12] R. K. Roy, *A primer on the Taguchi method*. Society of Manufacturing Engineers, 2010.

[13] Minitab 18 Support. (2019). Interpret the key results for Analyze Taguchi Design. [Online]. Available: https://support.minitab.com/en-us/minitab/18/help-and-how-to/modeling-statistics/doe/how to/taguchi/analyze-taguchi-design/interpret-the-results/key-results/