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► **To cite this version:**

Paul Lagouanelle, Van-Lang Krauth,, Lionel Pichon. Uncertainty Quantification in the Assessment of Human Exposure near Wireless Power Transfer Systems in Automotive Applications. AEIT AUTOMOTIVE 2019, Jul 2019, Turin, Italy. 10.23919/EETA.2019.8804593 . hal-02333919

HAL Id: hal-02333919

<https://hal.science/hal-02333919>

Submitted on 19 Aug 2020

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Uncertainty Quantification in the Assessment of Human Exposure near Wireless Power Transfer Systems in Automotive Applications

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Abstract – This paper addresses the uncertainty quantification of physical and geometrical material parameters in the design of wireless power transfer systems and in the assessment of the level of exposure for automotive applications. In a first step, Monte Carlo simulations are used to obtain the mean and confidence interval of the shielding effectiveness for conducting and composite materials over a wide frequency range in case of an academic shielding configuration. In a second step, a non-intrusive stochastic technique (Kriging) is combined with a 3D finite element method to study a simplified but realistic configuration of a power transfer system at 85 kHz. Such a prediction of uncertainties may help in the design of shields for inductive power transfer systems which comply with health and safety standards.

Keywords—EMC, Shielding effectiveness, Wireless power transfer, Uncertainty quantification

I. INTRODUCTION

In recent years, inductive power transfer (IPT) systems have been widely developed in several fields such as biomedical engineering, consumer electronics and the automotive industry. With such increased use, human exposure to the electromagnetic fields radiated by these systems in day to day life must be thoroughly investigated. The coupling between the transmitter, placed on the ground, and the receiver, placed under the vehicle floor, occurs through a large air-gap. This large gap implies a high level of stray field near the coils, that may represent a problem in terms of exposure to magnetic fields for passengers or people close to the vehicle during charging. It is therefore needed to design effective shielding materials to meet health and safety guidelines [1-4]. Furthermore, it is also important to evaluate the shielding effectiveness due to uncertainties in the electromagnetic and physical properties of a material; for instance, the electrical conductivity of new composite materials has a strong impact on the shielding effectiveness (SE) of sheets [5].

In order to assess human exposure near IPT systems in automotive applications, adequate modeling methodologies have to be developed. Nowadays 3D computational models are studied and applied to solve the electromagnetic problem involving the wireless system, the vehicle and the human body (in the vehicle or located beside) [3]. Such full wave computational approaches give reliable results about the radiated fields around the system or the induced quantities in the human body but may lead to heavy computations that must be repeated for each new configuration. A key point in

such problems is that the level of exposure is highly dependent on various parameters: the shape or size of coils, the geometrical characteristics of the system (structural parts of the vehicle, shielding plates), materials properties (ferrite, chassis of vehicle), the possible misalignment between transmitter and receiver while charging, the position of the human body. Moreover, each physical or geometrical parameter may be affected by some uncertainty. Therefore during the design of the IPT system, the consideration of the level of exposure cannot only rely on deterministic full 3D solvers. In such a situation the introduction of stochastic tools allows us to deal with the variability of all the parameters describing the electromagnetic problem. Such approaches were shown to be very efficient in the framework of the determination of specific rate absorption (SAR) in biological tissues due to mobile phones at microwaves frequencies [6,7]. Preliminary work demonstrated the interest of these stochastic techniques in IPT systems and underlined that Kriging appears a fast and reliable tool in such problems [8].

This paper studies the uncertainty propagation parameters in the predictions of radiated magnetic fields for a range of frequencies dealing with wireless power transfer. The first case considers a source loop in a low frequency range of 0-100kHz. Such standard geometry is a basic situation in IPT [9]. A Monte Carlo simulation [10] is then applied where a hundred tests were run at each frequency point. The mean of the results calculated is then plotted with the confidence interval against the frequency. Such study easily visualizes the uncertainties propagation effects on the shielding effectiveness in the case of different varying parameters. The second one involves a simplified but realistic inductive power transfer considered in [3]. With this configuration, Monte Carlo approaches are too costly, and a stochastic approach which only involves a limited set of samples provides a meta-model or surrogate model able to deal with the variability of the parameters. Kriging is also chosen due to its performances in electromagnetic compatibility problems.

II. SHIELDING OF CIRCULAR COIL

In the first electromagnetic problem, an analytical solution is available, and the shielding effectiveness is obtained at low cost. This allows us to achieve many calculations rapidly with a Monte Carlo simulation. The case of the circular loop has been studied in [11]. The model consists of a single planar shield lying in the x-y plane, parallel to a

current carrying loop also lying in the x-y plane, with radius “a” and centered at the origin. The shielding effectiveness is evaluated at some observation point along the z axis. Note that the distance between the shield and the observation point z does not affect the value of the shielding effectiveness.

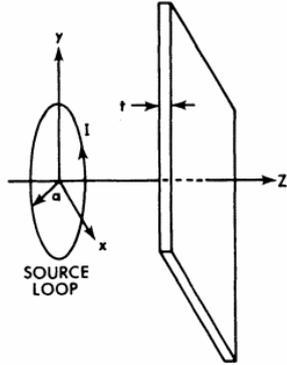


Fig. 1. Circular loop case [11]

The case of a 2 mm aluminum sheet with variable thickness (t) and conductivity is compared to the same system with a given thickness. The radius of the loop is a = 50 mm and SE is evaluated at z = 100 mm. The statistical properties are shown in Table I. Gaussian distributions are considered. While the mean of SE appears unaffected, figure 2 shows that a slight variance in the thickness results in a far larger standard deviation. This results in a confidence interval of SE which is approximately 10 dB.

TABLE I
STATISTICAL PROPERTIES

Input parameter	Mean	Standard deviation
Thickness (mm)	2	0.1
Conductivity (S/m)	3.8×10^7	7.4×10^5

Table 1. Statistical properties of input variables (loop case)

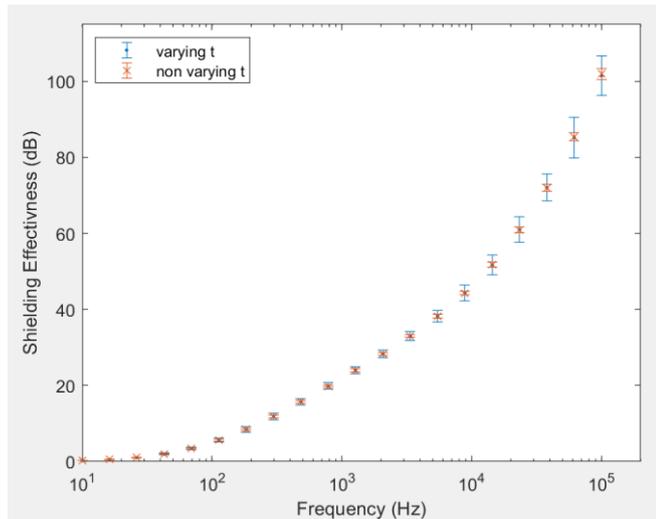


Fig. 2. Shielding effectiveness vs frequency for variant and non-variant thickness (t)

Such preliminary study is now expanded upon more complex systems using numerical electromagnetic models. Results will be presented at the conference.

III. WIRELESS POWER CONFIGURATION

A. Studied configuration

The structure model of the system considered in this work contains two rectangular coils (transmitter and receiver), and two ferrite plates [1,3]. The distance between the two coils is 0.25 m. The design also includes a steel plate that represents the chassis of the electric vehicle (Fig. 3). Previous studies have shown that such a simplified chassis is sufficient to evaluate its impact on the results. The dimensions of the system are shown on table 2.

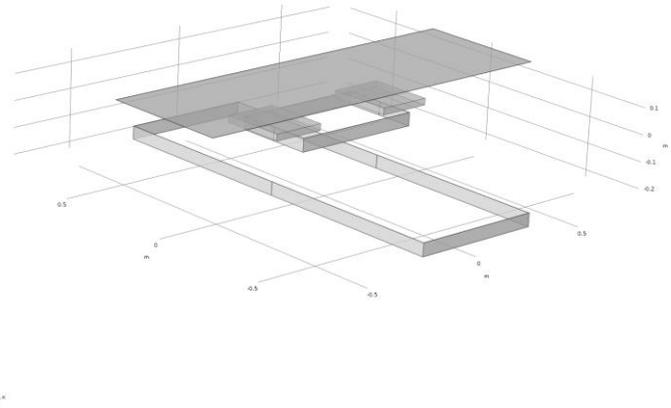


Fig. 3. Studied configuration of the wireless transfer system

TABLE II
DIMENSIONS

	Width (m)	Length (m)
Transmitter	0.5	1.5
Receiver	0.5	0.3
Ferrite	0.2	0.25
Frame	1.5	0.5

Table 2. Dimensions of the wireless power transfer system

The relative permeability of ferrite is 2200. Each coil has 10 turns. The magneto-dynamic problem is solved with a 3D vector potential formulation. This system has been designed for dynamic charging but in the present work only a static charging is considered. The power electronics controls and keeps the rms value of the current in the transmitter at 36 A and the current in the receiver at 75 A, respectively.

B. Kriging

Kriging is a stochastic interpolation algorithm which assumes that the model output $M(x)$ is a realization of a Gaussian process indexed by the inputs x . A Kriging meta-model is described by the following equation [12]:

$$M(x) \sim M^K(x) = \beta^T f(x) + \sigma^2 Z(x, \omega) \quad (1)$$

The first term in (1), is the mean value of the Gaussian process (trend) and it consists of the regression coefficients β_j ($j = 1, \dots, P$) and the basis functions f_j ($j = 1, \dots, P$). The second term in (1) consists of σ^2 , the (constant) variance of the Gaussian process and $Z(x, \omega)$, a zero mean, unit

variance, stationary Gaussian process. The underlying probability space is represented by ω and is defined in terms of a correlation function R and its hyper-parameters θ . The correlation function $R = R(x; x_0; \theta)$ describes the correlation between two samples of the input space, *e.g.* x and x_0 and depends on the hyperparameters θ . In the context of meta-modelling, it is of interest to calculate a prediction $M^K(x)$ for a new point x , given $X = (x_1, \dots, x_n)$, the experimental design and $y = (y_1 = M(x_1), \dots, y_n = M(x_n))$, the corresponding (noise-free) model responses. A Kriging meta-model (Kriging predictor) provides such predictions based on the Gaussian properties of the process.

The meta-model described above and used in this paper was developed in [12] and proposed in the framework for uncertainty quantification freely available.

IV. NUMERICAL RESULTS AND DISCUSSION

Kriging has been applied in the configuration of Fig. 3. to check the compliance regarding the references levels of the radiated magnetic field. For the frequency of interest (85 kHz), the maximum admissible value of the magnetic flux density is 27 μ T according to the ICNIRP Guidelines (2010).

A. First case – 1 parameter (frame conductivity)

In a first example, the uncertainty regarding the frame conductivity is investigated. The range of variation is shown in table III. It covers both the case of composite materials (with low conductivity) and standard conducting materials. The 3D finite element mesh includes between 80000 and 90000 elements. First order nodal elements are used in the method.

TABLE III
PARAMETERS OF THE ELECTROMAGNETIC PROBLEM

Parameter	Min	Max
σ (S/m)	10^4	10^6

Table 3. Range of variation of the parameter

In order to check the efficiency of the meta-models, a total number of 15 computations is performed by FEM (COMSOL) based on a uniform logarithmic distribution of samples over the whole range of variations. Fig. 5. shows the mean of the flux density and the confidence interval provided by the meta-model in a point located at 50 cm near the frame representing the possible location of a bystander (red point on Fig.4).

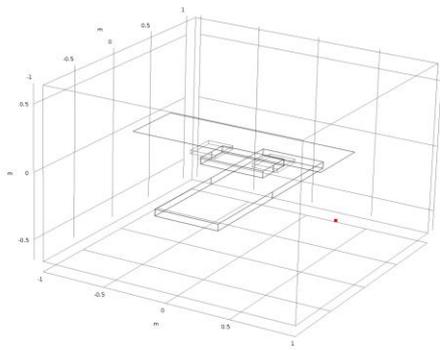


Fig. 4. Location of the observation point (red point)

The magnitude of the prediction is clearly exceeding the threshold (27 μ T). The accuracy of the meta-model is checked thanks to the LOO (leave-one-out) cross-validation provided by Kriging and defined according to [12]:

$$E_{00} = \sum_{i=1}^N (M(x_i) - \mu_{\hat{Y},(-i)}(x_i))^2 / \text{Var}[Y]$$

This quantity involves in each sampling point x_i the error between the value provided by the model and the Kriging prediction by using all the sampling points except x_i .

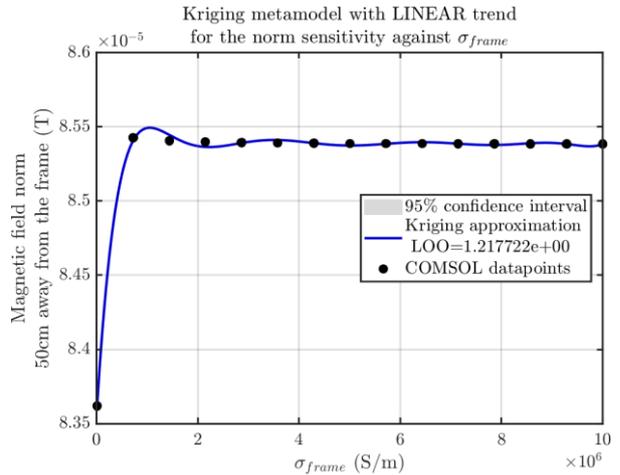


Fig. 5. Predictions of Kriging from the basis of 15 samples

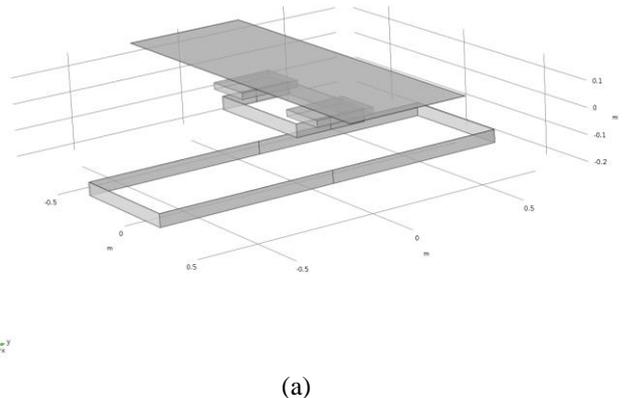
B. Second case – 2 parameters (frame conductivity and misalignment between emitter and receiver)

In this second configuration the first parameter σ is the same than in IV.A and the second parameter D is the distance between the two axes of the coils (Fig. 6). This configuration may appear in case of large misalignment or if the receiver is located in the rear of the vehicle. The range of variations of the two parameters is given on table IV.

TABLE IV
PARAMETERS OF THE ELECTROMAGNETIC PROBLEM

Parameter	Min	Max
σ (S/m)	10^4	10^6
D (m)	0.	0.5

Table 4. Range of variation of the parameter



(a)

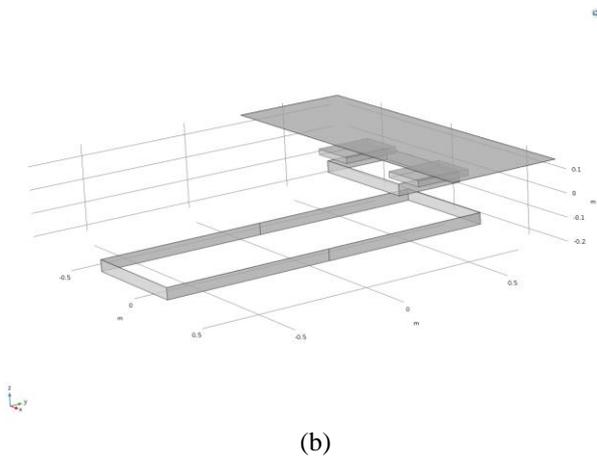


Fig. 6. Configuration with a misalignment of 0 cm (a) and 50 cm (b).

In this case, a total number of 100 samples are chosen (10 values for each of the two parameters). The same observation point is located (Fig.4). Fig. 7 and shows the plot of the flux density versus the two parameters. In this instance the reference level of 27 μT is mainly and strongly dependent on the distance parameter.

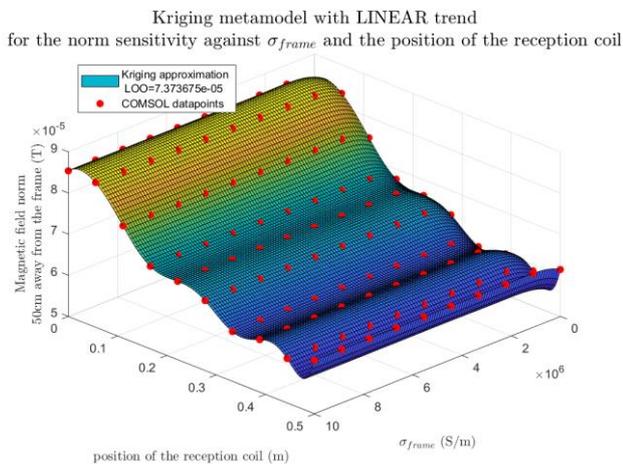


Fig. 7. 2D plot of the flux density for 100 sample data

Fig. 8 displays a 2D plot when the number of samples is reduced to 25 (5 x 5). The global behavior of the observable quantity is very well predicted from a few numbers of values.

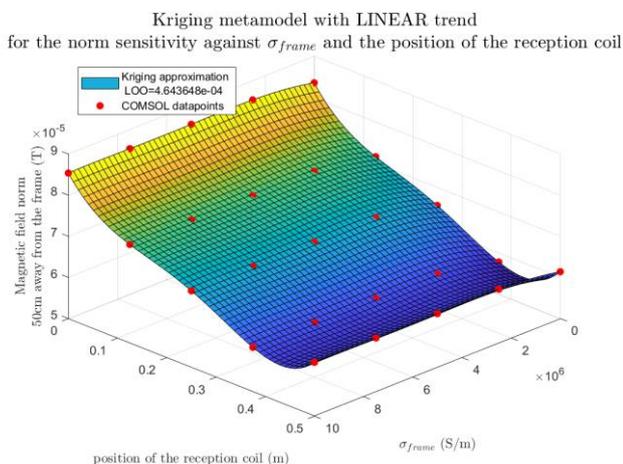


Fig. 8. 2D plot of the flux density for 25 sample data

V. CONCLUSION

Predictions of the radiated magnetic field have been obtained from a statistic approach and stochastic model (Kriging) in case of simplified but realistic wireless power transfer systems for electric vehicles. Kriging provides efficient meta-models to consider the uncertainties of different physical or geometrical parameters. Provided that the number of samples is sufficient, Kriging can be used as an efficient predictor to check if reference levels fit the guidelines for human exposure. The work is now extended to investigate more complex configurations taking into account the global structure of the vehicle and anatomical models of the human body.

ACKNOWLEDGMENT

The results here presented are developed in the framework of the 16ENG08 MICEV Project. The latter received funding from the EMPIR program co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation program.

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