Computational Dosimetry for Wireless Charging of an Electrical Vehicle

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***Abstract*—Recent advances in wireless power transmission have enabled various new applications, one of which is wireless charging of an electrical vehicle. In this application, electric power is wirelessly transmitted using strong electromagnetic fields from a coil located on the ground to another coil attached to the vehicle. In this study, we use computational modelling to investigate the human exposure to the electromagnetic fields of such a wireless charging system. The transmitted power is 7 kW and the frequency of power transmission is 85 kHz. The strengths of the external magnetic field around the vehicle and the electric field induced in the human body are compared with the exposure limits set in the international human exposure guidelines. It is found that the magnetic field strength near the vehicle exceeds the allowable field limits of international guidelines. However, the electric fields that are induced in the human body are well below the exposure limits. Therefore, kW-class wireless charging of an electrical vehicle seems to be feasible for general public use from the point of view of human exposure.**

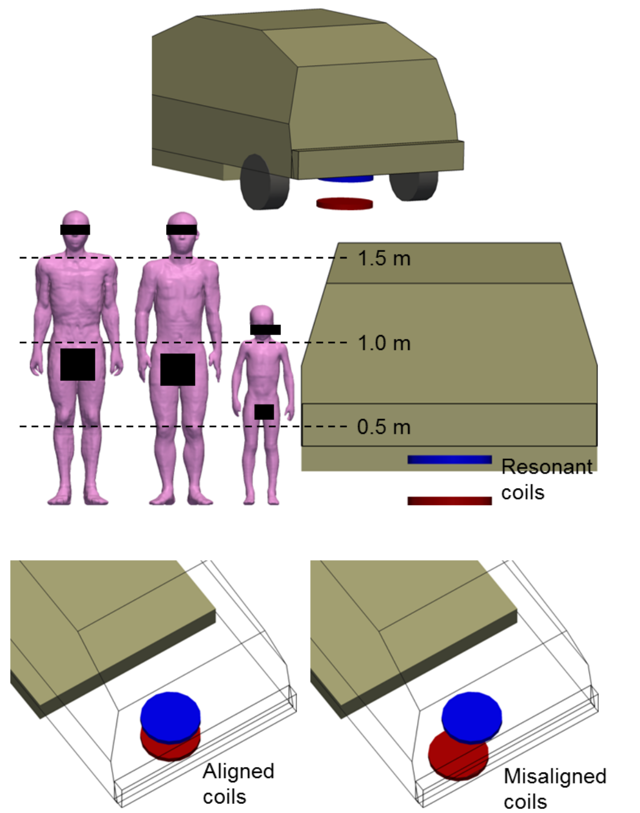

Fig. 1. Geometry of the vehicle and the wireless power transmission system. Anatomical models are shown standing next to the vehicle, from left to right: NORMAN, TARO, and Thelonious.

I. Introduction

Magnetic resonant coupling between two coils allows effective wireless transmission of power over distances in the range of tens of centimetres to a few metres [1], [2]. Many research institutes and companies have been actively developing wireless power transmission (WPT) systems since the technique was pioneered in 2006 by a research team at Massachusetts Institute Technology [1]. Innovative new technologies that use WPT have the potential to improve our everyday life. However, questions remain about the exposure of humans to the electromagnetic fields used in WPT systems.

One potential application of WPT is charging of an electrical vehicle. In this application, the transmitted power is several kilowatts, which produces strong magnetic fields near the vehicle. When users or bystanders are moving in the vicinity of the vehicle, these strong magnetic fields can induce significant electric fields and currents in the body. This raises concerns about the safety of this kind of a WPT system for general public use. To alleviate these concerns, this study presents a detailed evaluation of human exposure for a WPT system that has been proposed for charging of an electrical vehicle.

Several international guidelines and standards limit the human exposure to electromagnetic fields [3]–[5]. In this work, we will consider the human exposure guidelines developed by the International commission on non-ionizing radiation protection (ICNIRP) [3], [4]. In these guidelines, there are two kinds of exposure limits: the *reference levels*, which are given in terms of the strength of the external electromagnetic field, and *basic restrictions*, which are defined in terms of the strength of the fields inside the body. If the reference levels are exceeded, then it is necessary to investigate whether the basic restrictions are satisfied. This investigation requires the use of computational modelling of the electromagnetic fields in the human body.

Until now, few studies have computationally investigated human exposure to electromagnetic fields of WPT systems [6]–[9]. All of these studies considered similar kinds of idealized models of WPT systems whose operating (resonant) frequency was at around 10 MHz. In this study, we investigate a different type of resonant WPT system whose operating frequency is 85 kHz. A significant difference to previous studies is that the *induced electric field* is used as the exposure metric that should be compared with the basic restrictions [4]. In previous studies, which considered higher frequencies, the exposure metric was the specific energy absorption rate (SAR).

II. Methods and Models

A. Vehicle and Power Transmission System

A simplified model for the electrical vehicle that consisted of perfect electrical conductor was considered. The wireless power transmission system consisted of two coils that were located below the rear of the vehicle and was modelled based on a prototype system that was investigated experimentally in [10]. One coil, the transmitting coil, was located on the ground, and the other coil, the receiving coil, was attached to the vehicle. The distance between the coils was 15 cm. The frequency of power transmission was 85 kHz, and the waveform of the coil current was assumed to be sinusoidal. The transmitted power was normalized to 7 kW (rms). Two different scenarios were considered (Fig. 1). In the first scenario, the positions of the coils were aligned in the horizontal direction, i.e., the vehicle coil was located directly above the ground coil. In the second scenario, the ground coil was moved 10 cm to the rear and 20 cm to the left. The latter scenario produces a worse power transmission efficiency and a larger external magnetic field.

B. Numerical Body Models

Three numerical anatomical human body models were considered (Fig. 1). They were NORMAN [11] (adult male, height 176 cm, weight 73 kg), TARO [12] (adult male, 173 cm, 65 kg), and Thelonious [13] (6-year old male, 117 cm, 20 kg). The models consist of three-dimensional segmented representation of several tissues/organs and body fluids. The electrical properties of each tissue/body fluid were modelled using the fourth order Cole–Cole model of [14].

C. Computational Methods

A quasi-static "two-step" approach was used for determining the induced electric fields in the human body [6]. With this approach, it is assumed that the electric field induced in the body by the electric field of the WPT system is negligible, so that the fields induced in the body are produced entirely by the magnetic field. Additionally, it is assumed that the human body does not perturb the external magnetic field, which has been shown to be a good approximation for frequencies up to the 10 MHz band [6], [7].

The resonant coils and the vehicle were first modelled using HFSS (Ansys, Inc) without considering the presence of the human body, and the magnetic field distribution around the vehicle was determined. This magnetic field distribution was then imported to an in-house computer code written in MATLAB and C programming language, and the induced electric fields were determined in the anatomical body models. The in-house code utilizes the quasi-static finite element method and it has been described in detail in [15]. The elements were uniform and cubical with a side length of 2 mm.

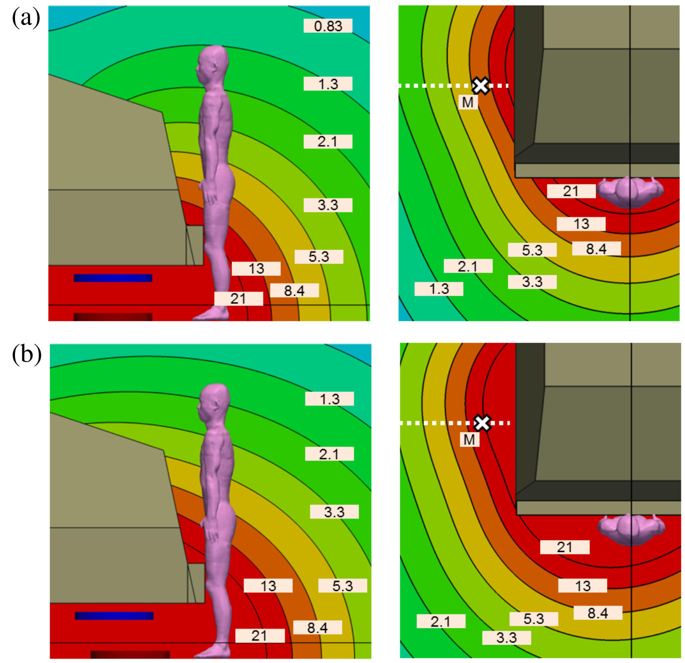

Fig. 2. The strength of the magnetic field around the rear of the vehicle in the cases of (a) aligned coils and (b) misaligned coils when the transmitted power is 7 kW (rms). The magnetic field values are given in A/m (rms). Left column: magnetic field on the plane of the centreline of the vehicle. Right column: magnetic field on a horizontal plane at a height of 10 cm above the ground. The computed results were compared to the measured results at the location marked by M (Fig. 3).

D. Exposure Metric

The ICNIRP guidelines [4] use the 99th percentile electric field value as the metric for the exposure. This value should be compared with the basic restrictions. The 99th percentile electric field value is calculated by removing highest 1% of electric field values in each tissue type from consideration, and then taking the maximum value. The rationale for this metric is to remove numerical errors that cause unrealistic "hot spots" in the computed electric field. These hot spots are thought to be contained in 1% of voxels with the highest of electric fields.

III. Results

A. Magnetic Field Around the Vehicle

The magnetic field distribution around the vehicle was determined using HFSS (Ansys, Inc), and it is shown in Fig. 2. The magnitude and distribution of the computed magnetic field were verified to be in good agreement with measured results for a similar kind of system (Fig. 3). As seen in Fig. 2, the magnetic field strength around the models' legs exceeds the ICNIRP reference level of 21 A/m (rms) for the external magnetic field.

The position of the body shown in Fig. 2 presents the worst-case position that gave both the highest average and maximum magnetic fields in the body. In the adult models, the *average*

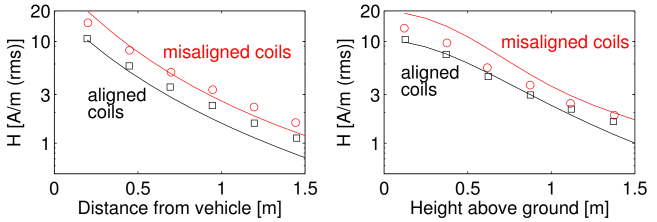

Fig. 3. Comparison between measured (markers) and computed (solid lines) magnetic fields on horizontal (left) and vertical (right) lines at the location marked by M in Fig. 2. The measured data have been obtained by scaling the results for a 3 kW power transmission system from [10].

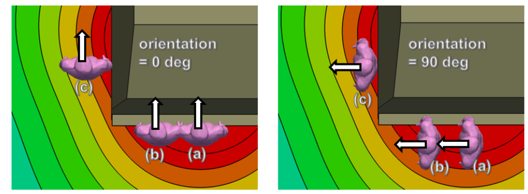

Fig. 4. Positions of the body. The orientation of the model was varied in steps of 45°. For each body orientation, the distance between the body and the vehicle was tuned so that the body just barely touched the vehicle.

magnetic field over the whole body was at most 10 A/m or 14 A/m for the cases of aligned and misaligned coils, respectively. In the child model, the corresponding average magnetic fields were 15 A/m and 22 A/m, the latter of which exceeds the ICNIRP reference level. The *maximum pointwise* magnetic field strengths considerably exceeded the ICNIRP reference levels in the toes of all three models: they were at most 90 A/m and 180 A/m for the cases of aligned and misaligned coils, respectively.

B. Induced Electric Fields

The induced electric fields in the body were determined for three positions of the human body, which are shown in Fig. 4. At each position, the orientation of the body was varied in steps of 45°. Hence, the total number of cases studied was 144 (misaligned and aligned coils, three human body models, three body positions, and eight body orientations).

Figure 5 shows the strength of the electric fields induced in the body for different body orientations and positions with respect to the vehicle. It can be seen that the induced electric fields were the highest when the human body is standing directly behind the vehicle (position (a)). The body orientation that resulted in the highest electric field varied depending on the body model and its position with respect to the vehicle. It is important to note that the induced electric field was the *weakest* in the child model, even though the average magnetic field strength was much stronger than in the adult models. In both adult models, the induced electric fields were comparable.

At the frequency of 85 kHz, the ICNIRP basic restriction for general public exposure is 11.5 V/m (rms). From Fig. 5, the induced electric field was at most 2.3 V/m (in the case of misaligned coils in the TARO model), which is 80% less than the basic restriction.

Figure 6 shows the dependency of the induced electric field on the distance between the vehicle and the human body. The electric field is reduced to roughly one half when the distance increases from 0 cm (body touching the rear bumper) to 50 cm.

IV. Discussion

The induced electric fields were studied in three different anatomical models of the human body that were located at various positions near the vehicle. In all cases studied herein, the induced electric field was less than 2.3 V/m when the

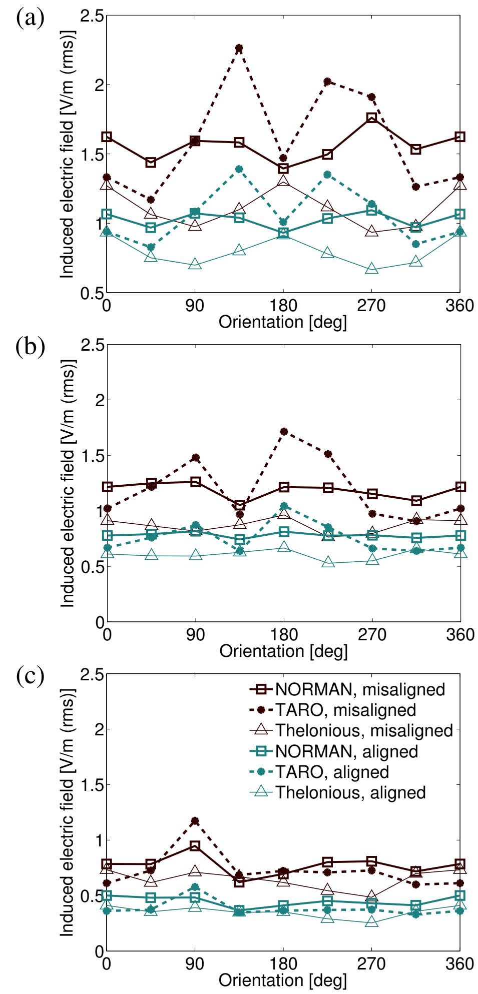

Fig. 5. The induced electric field for body positions (a), (b), and (c) in Fig. 4.

transmitted power was 7 kW. This value is well below the ICNIRP basic restriction of 11.5 V/m (rms). It is important to note that the electric field induced in the body is directly proportional to the square root of the transmitted electric power. For instance, if the transmitted power is halved from 7 kW, the induced electric field will decrease by 30 %.

The induced electric fields were weaker in the child model than in the adult models. This is likely due to the smaller size of the child model which results in a smaller magnetic flux that flows through the body. It should be noted that, because the child model was much shorter than the adult models, the

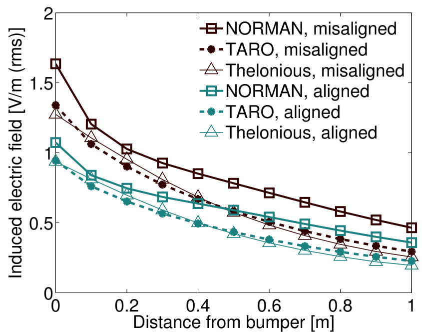

Fig. 6. Induced electric field as a function of distance from the rear bumper. The body is located at position (a) and faces the front of the vehicle (orientation = 0°).

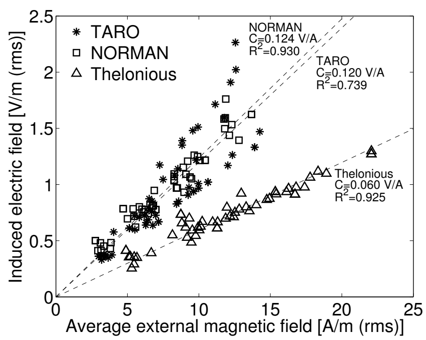

Fig. 7. Induced electric field as a function of the magnetic field averaged over the whole body. The dashed lines show linear least squares fits to the data together with the slope (C) and coefficient of determination (R^2).

average strength of the magnetic field in the volume occupied by the body was higher. Therefore, it is clear that it is not only the strength of the external magnetic field that is important; also the size of the body matters.

The external magnetic fields exceeded the ICNIRP reference levels locally in the feet and lower legs. The reference level is defined for an exposure to a uniform magnetic field. Therefore, it is not directly applicable to the nonuniform case considered in this study. Figure 7 shows that, in the scenarios considered herein, the ratio between the induced electric field and the external magnetic field averaged over the whole body was 0.12 V/A for the adult models and 0.06 V/A for the child model. Therefore, if the average magnetic field over the body is less than the reference level of 21 A/m, then the basic restriction of 11.5 V/m is well satisfied. Hence, the average magnetic field over the whole body appears to be a conservative exposure metric that can be directly compared with the reference level to ensure that the basic restriction is satisfied. The advantage of this metric is that it can be estimated using magnetic field measurements without the need for computational modelling.

In conclusion, this study investigated for the first time human exposure to the electromagnetic fields of a wireless power transmission system operating at a frequency of 85 kHz. The transmitted electromagnetic power was 7 kW, which is much higher than the powers used in any previous wireless applications that are available to the public. Still, the induced electric fields in the body were found to be well below the basic restrictions of international exposure guidelines in all studied scenarios. Thus, high-power wireless charging of an electrical vehicle is feasible for general public use from the point of view of human exposure. Nonetheless, while the induced electric fields were smaller than the basic restrictions, they still were within the same order of magnitude. Further exposure assessment of wireless power transmission systems is thus necessary before the technology can be deployed widely.

ACKNOWLEDGEMENT

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