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Investigation on the human body exposure to the magnetic fields owing to wireless power transmission system with the sandwiched structure

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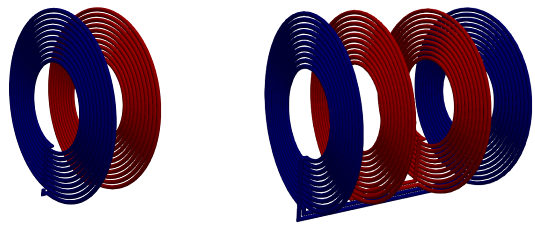
Abstract

Currently, a "sandwiched structure" has been proposed for the wireless power transmission system, which is suitable for personal mobility. The sandwiched structure is constructed by two power receiving coils and two power transmission coils. The two power receiving coils are sandwiched between two power transmission coils. This structure stabilizes power transmission, regardless of changes in position for the power receiving coils to the power transmission coils. In this paper, induced electric fields in the human body are calculated under the exposure of 85 kHz magnetic fields generated by sandwiched structure and conventional structure. Accordingly, it was found that when the same power is transmitted, the median value of induced electric field is reduced by the sandwiched structure rather than by the conventional structure.

1 Introduction

Recently, the share cycle of electrically power assisted bicycles has become widespread in urban areas in Japan. Battery charging is indispensable when using an electrically power assisted bicycle. In the current charging situation, it is necessary to remove the battery from the bicycle, connect the battery to the charger, and then attach it to the bicycle. However, problems, including battery fall accident, battery theft, or poor contact owing to the deterioration of terminals, may occur. Thus, measures, such as installing a power suppling device on the bicycle parking stand and integrating the bicycle with the battery, have been considered. In addition, it is convenient to develop a wireless power transfer device because it does not produce electric shock, especially, when the charging environment is an outdoor or in the rain.

Currently, a "sandwiched structure"[1] has been proposed for the wireless power transmission (WPT) system, which is suitable for personal mobility. In conventional WPT system, power is transmitted using a pair of power transmission and receiving coils, as shown in Figure 1(a). In this new structure, as shown in Figure 1(b), there are two power receiving coils indicated in red that are sandwiched by two power transmission coils indicated in blue. Figure 2 shows the sandwiched structure being applied to an electrically



(a) Conventional structure **(b)** Sandwiched structure

Figure 1. Comparison of two types of coil

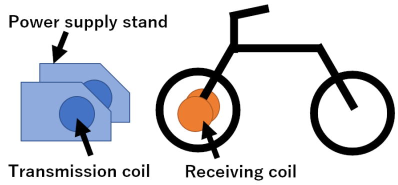
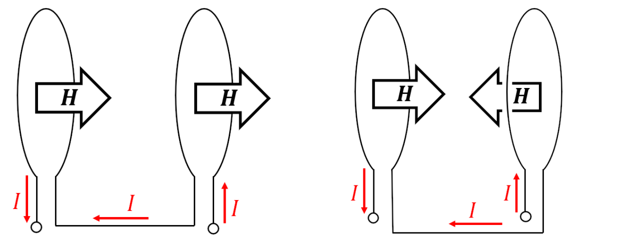


Figure 2. The example of applying the sandwiched structure to an electrically power assisted bicycle

assisted bicycle. Using this structure, it is shown by experiment that the robustness to changes in the position of the power receiving coil in the central axis direction is improved compared to the conventional coil structure. In the sandwiched structure, four coils are used to supply power. Therefore, it is possible that there are multiple magnetic field configuration modes depending on the polarity of the coils. However, currently, the magnetic field configuration mode with respect to the sandwich structure has not been clarified. Furthermore, there is concern about the health effect of the magnetic field generated by the WPT device on the human body. A magnetic field is generated from the coil during the power supply of the WPT, and the electric field is induced by the coupling between the magnetic field and the body.

However, the dosimetry of the induced electric field generated from the magnetic field by sandwiched structure device has not been performed yet. It is difficult to measure the induced electric field in the human body, because of physical and ethical issues. In this study, the induced electric field in the body was calculated by numerical calculation. Therefore, this study aims to clarify the magnetic field configuration mode for sandwiched structure, calculate the magnetic



(a) Cumulatively coupled coils **(b)** Differentially coupled coils

Figure 3. Coupling of coils connected in series

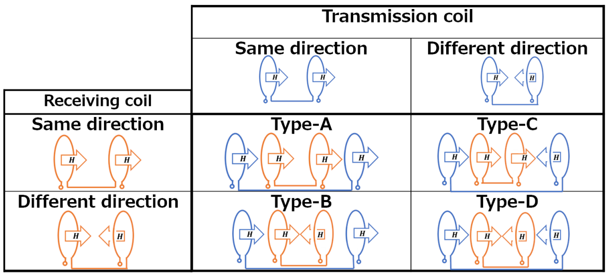


Figure 4. Magnetic field configuration modes of sandwiched structure

field in each mode, and calculate the induced electric field for magnetic field exposure.

2 Magnetic field generated by sandwiched coil structure

2.1 Magnetic field configuration mode

In this section, the magnetic field distributions of the conventional structure and the sandwiched structure are discussed before calculating the magnetic fields. Because WPT with the sandwiched structure uses four coils to transmit power, as shown in Figure 1(b), there exist multiple magnetic field configuration modes. The magnetic fields that are generated by the transmission coils or the receiving coils induced in the sandwiched structure are composed of coils in the same direction (cumulatively coupled), as shown in Figure 3(a), or different direction coils (differentially coupled), as shown in Figure 3(b), respectively. Because these two conditions are applied for each transmission coil and receiving coil, respectively, the sandwiched structure has four modes in total, as shown in Figure 4. In Figure 4, type-B and type-C modes are not considered this study. This is because the induced electromotive forces generated by the two receiving coils cancel each other, and it is impossible to perform power transfer. Therefore, we consider type-A modes and type-D sandwiched structures that can transmit power.

2.2 Calculation of magnetic fields

The magnetic fields generated by the conventional and sandwiched coil structures are calculated. Simulation conditions are shown in Table 1.

Table 1. Simulation conditions

Simulation software	CST EM STUDIO (Ver.2019.00)
Simulation method	Finite integral method (Frequency domain)
Boundary condition	Open boundary
Accuracy	1×10^{-4}
Frequency	85 kHz
Spatial mesh structure	Tetrahedral mesh

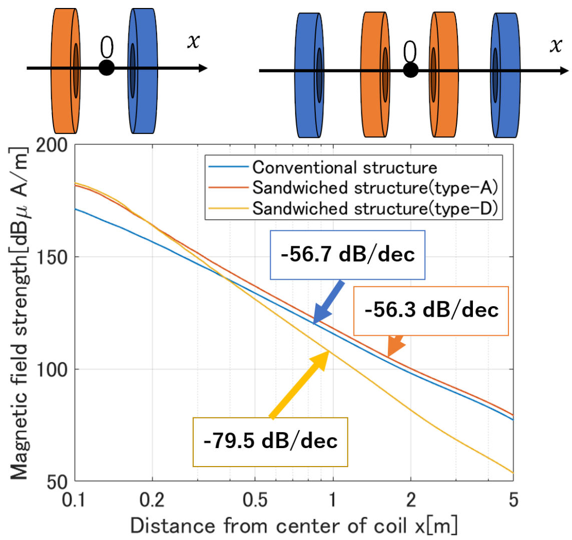


Figure 5. Distance characteristics of each magnetic field strength

Figure 5 shows that the decay of each magnetic field strength depend on the distance from the origin of coordinate along the x axis direction. The horizontal and vertical axes represent the distance and the magnitude of magnetic fields, respectively. It seems that all the magnetic field strengths decay linearly depending on the increase of the distance larger than approximately 0.5 m. The magnitude of magnetic fields decays at a rate of -56.7 and -56.3 dB/dec for the conventional type-and the sandwiched structure type-A, respectively, while -79.5 dB/dec for type-D. The magnetic field strength owing to type-D decays with a larger inclination than the rest coil structures because the transmission coils and the receiving coils generate opposite directions of the magnetic fields; thus, cancelling each other. Therefore, the magnetic field leakages are efficiently suppressed.

3 Dosimetry induced electric field in the human body

Currently, a frequency of 85 kHz is examined in the development of sandwiched structure WPT systems. The dominant biological effect caused by the magnetic field in the 85 kHz band is nerve stimulation. Therefore, the induced electric field strength in the human body is used as an index for evaluating exposure [2].

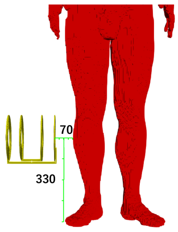


Figure 6. Separate 7cm

Table 2. Simulation conditions

Frequency	85 kHz
Transmission power	500 W
Length of a voxel	2 mm
Number of voxels in calculation domain	44,339,200
Number of voxels in the body	8,049,016

In this study, exposure scenario is assumed as follows. The human body approaches the WPT systems during power supply. The induced electric fields are estimated when the human body is exposed to the magnetic field under the operation of the WPT systems. We used the three-dimensional impedance method [3, 4] for the induced electric field simulation, and the magnetic fields calculated in the previous section was used for the incident field.

The power receiving coil is installed on an electrically power assisted bicycle with a tire diameter of 26 inches ($\simeq$66 cm) to ensure that the central axis of the coil is 330 mm from the ground. The end of the coil was set at a position 70 mm from the side of the right calf of the TARO model, as shown in Figure 6. Three configurations of magnetic fields owing to the conventional structure and the sandwiched structure type-A and type-D structures are considered in performing simulations.

3.1 Conditions of the simulation

Simulation conditions are shown in Table 2. In addition, we used the SOR method [5] as the solution for simultaneous linear equations, and the relative residual norm was set to $< 1 \times 10^{-4}$ as the convergence condition. Each tissue in the TARO model was assigned the value of suitable complex permittivity at 85 kHz by referring to [6].

3.2 Simulation results

Figure 7 shows the Induced Electric Field Strength (IEFS) in the cross section of coronal plane. The magnetic field exposure by conventional structure and sandwiched structure type-A has a similar distribution of IEFS in the whole human body. However, the IEFS in the body owing to the sandwiched structure type-D is smaller than those owing to the other two structures. In particular, type-D has smaller IEFS in the upper body part.

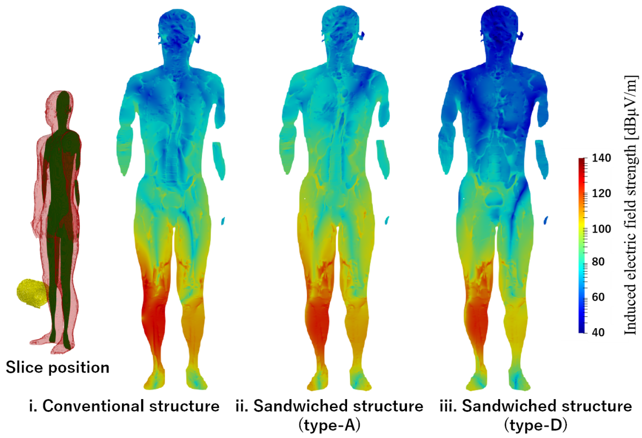


Figure 7. IEFS in the cross section of coronal plane

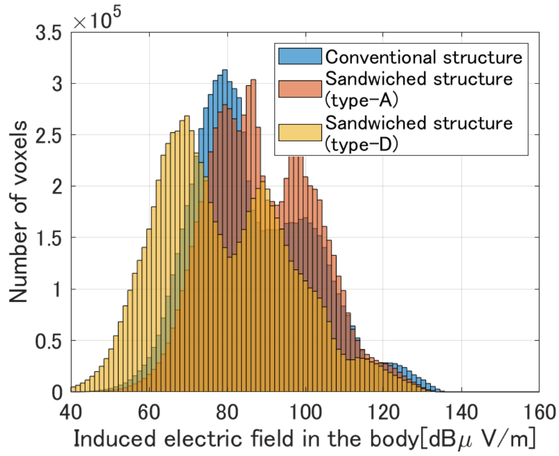


Figure 8. Histogram of IEFS in the body (70 mm)

Figure 8 shows histograms of the IEFS in the human body. Table 3 shows the 99.9th percentile value, the 99th percentile value, and the median value of IEFS in the human body for three cases. In the histogram, the conventional structure and type-A of the sandwiched structure have the tendency to be induced with larger electric fields than that for type-D. The median value of the IEFS in the body owing to the sandwiched structure type-D is approximately 7.1 dB smaller than the conventional structure. Therefore, the amount of exposure is more reduced when using sandwiched structure type-D than when using the conventional structure.

The values of the 99.9th percentile are compared with the ICNIRP basic restriction value for the general public exposure at 85 kHz. In these three cases, the 99.9th percentile of IEFSs does not exceed the basic restriction value of 141.2 dBμV/m.

4 Conclusion

In this study, we calculated the magnetic field generated from a sandwiched structure and a conventional structure.

Table 3. Statistical data of IEFS in the body (70 mm)

	99.9%ile (dBμV/m)	99%ile (dBμV/m)	Median (dBμV/m)
General	132.3	126.0	83.5
Sandwiched (type-A)	129.7	123.1	87.5
Sandwiched (type-D)	129.0	121.6	76.4

It was shown that the sandwich structure can have four magnetic-field configuration modes, as two of these modes do not transmit power. The remaining two types were analyzed. The magnetic field lines have different shapes in type-A and type-D modes. However, type-A shows a similar magnetic field line distribution as the conventional structure. The magnetic field line of type-D does not cover a large region and fits into a compact area close to the coils. The magnetic field strength for the conventional structure and the sandwiched structure type-A decay at a rate of -60 dB/dec depending on the increase in distance from the coils. The rate of decay for type-D is -80 dB/dec, larger than that of type-A and type-D.

Next, we calculated the induced electric field in the human body when it approached the conventional structure coil or the sandwiched structure coil during 500 W power supply using the three-dimensional impedance method. The results indicated that the 99.9th and 99th percentile values are smaller in the sandwiched structure than in the conventional structure. In addition, the electric field induced to the upper body, where important organs are located, is significantly smaller when using the sandwiched structure of type-D than that in the conventional structure. The median value of the IEFS in the body for the sandwiched structure of type-D is 7.1 dB smaller than that for the conventional structure when the coils are separated by 70 mm from the human body. However, when compared with the 99.9th percentile value, there is no significant difference between the sandwiched structure type-D and the conventional structure. The values of the 99.9th percentile for the three cases do not exceed the basic restriction of general public exposure in all cases.

The future prospects are to perform magnetic field distribution analysis and induced electric field calculation in the misaligned situation of the receiving coil.

References

[1] Misato Akiyama, Hiroyasu Sano, and Manabu Omori, "Development of wireless power transfer antenna by sandwiched structure," The Japan Society of Applied Electromagnetics and Mechanics, vol.25, no.4, pp.403–408, 2017. in Japanese.

[2] International Commission on Non-Ionizing Radiation Protection and others, "Guidelines for limiting exposure to time-varying electric and magnetic fields (1 hz to 100 khz)," Health physics, vol.99, no.6, pp.818–836, 2010.

[3] N. Orcutt and O.P. Gandhi, "A 3-d impedance method to calculate power deposition in biological bodies subjected to time varying magnetic fields," IEEE Transactions on Biomedical Engineering, vol.35, no.8, pp.577–583, 1988.

[4] O.P. Gandhi, J.F. Deford, and H. Kanai, "Impedence method for calculation of power deposition patterns in magnetically induced hyperthermia," IEEE Transactions on Biomedical Engineering, vol.31, no.10, pp.644–651, 8 1984.

[5] R. Barrett, M. Berry, T.F. Chan, J. Demmel, J. Donato, J. Dongarra, V. Eijkhout, R. Pozo, C. Romine, and H. Van der Vorst, Templates for the solution of linear systems: building blocks for iterative methods, SIAM, 1994.

[6] S. Gabriel, R. Lau, and C. Gabriel, "The dielectric properties of biological tissues: Iii. parametric models for the dielectric spectrum of tissues," Physics in medicine & biology, vol.41, no.11, p.2271, 1996.