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FDTD Analysis for Protecting Human Body from Electromagnetic Wave Using Thin Resistive Sheet

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SUMMARY

From the practical point of view, conductive film materials that are thin and flexible are chosen as practical shielding materials, and their shielding effect is studied. In the analysis, the concept of equivalent surface resistivity is applied to the FDTD method. The effectiveness of this method in the analysis of absorbed power of the electromagnetic wave in the human body is investigated. The effectiveness of this method for this type of analysis is confirmed. In addition, the shield effect is quantitatively evaluated in terms of the variation of the surface resistivity of the conductive film. It is shown that a resonance phenomenon occurs when the shield effect varies depending on the distance between the human models. It is observed that in such a situation the electromagnetic wave is concentrated in the front surface of illumination so that a large local SAR appears. © 2000 Scripta Technica, Electron Comm Jpn Pt 1, 83(9): 86–92, 2000

Key words: Shield; SAR; FDTD.

1. Introduction

As unwanted electromagnetic waves emitted from electrical equipment, such as mobile communication gears, increase, research has been carried out for protection of the human body from the electromagnetic waves [1, 2].

From a practical point of view, the authors have chosen thin and flexible lossy materials, such as conductive films, for practical and realistic shield materials. By means of the mode matching method, the shield effect has been investigated in the case where this conductive film is placed in front of a cylindrical human body model [3].

Based on this research background, the concept of the equivalent surface resistivity of the conductive film proposed by Shimizu and Nagao [4] is applied in this article to the FDTD method. Assuming the case in which the film is placed in front of the body like an apron, the shield effect is studied for various shapes and shield range of the conductive film.

In the analysis of the absorbed power of the electromagnetic wave in the body, it is shown that study of the shield effect is possible by means of the FDTD method for a conductive film used as a shield material. It is investigated quantitatively, including the resonance phenomenon in which the shield effect varies significantly with the surface resistivity of the conductive film and with the distance between the material and the body. When a resonance occurs, it is found that the electromagnetic field is concentrated in the front surface where the electromagnetic wave is incident, so that a large local SAR appears.

2. Analysis Model

As an example of the analysis model, the cross section of a homogeneous cylindrical human body with infinite length along the z-axis is shown in Fig. 1. AREA 1 is the human body, while AREA 2 and AREA 3 are the air layers (free space). As seen, a conductive film (shield material) of elliptical shape is placed in front of the human body. In the

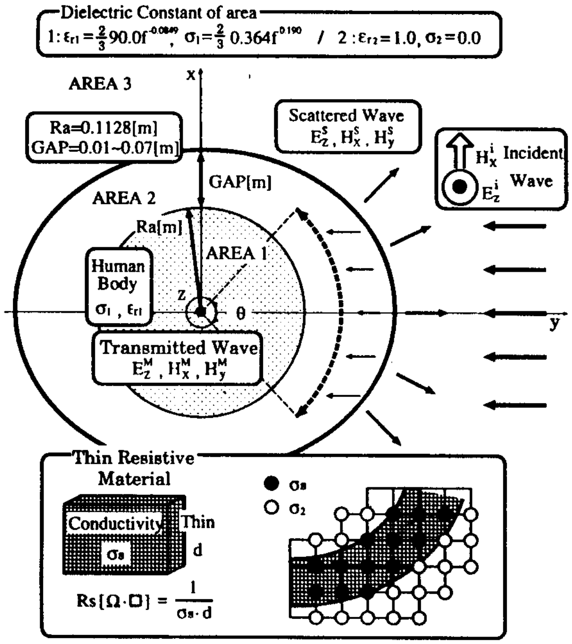

Fig. 1. Human body model with cylindrical cross section surrounded by an oval shield.

present research, the total body average SAR and the local SAR are analyzed in the case where a plane wave (TM wave) with an electric field component along the z-axis (E_z^i), considered important for the human effect, is incident in the $-y$ direction.

In the analysis method, the electromagnetic field ($\boldsymbol{E}^t$, $\boldsymbol{H}^t$) in the analysis domain in Fig. 1 is decomposed to the incident component ($\boldsymbol{E}^i$, $\boldsymbol{H}^i$) and the reflected component ($\boldsymbol{E}^s$, $\boldsymbol{H}^s$) [5]:

$$\boldsymbol{E}^t = \boldsymbol{E}^i + \boldsymbol{E}^s \tag{1}$$

$$\boldsymbol{H}^t = \boldsymbol{H}^i + \boldsymbol{H}^s \tag{2}$$

Also, the incident electric field $\boldsymbol{E}^i$ and the incident magnetic field $\boldsymbol{H}^i$ satisfy the following equations not only in free space but also in the lossy medium:

$$\nabla \times \boldsymbol{E}^i = -\mu_0 \frac{\partial}{\partial t} \boldsymbol{H}^i \tag{3}$$

$$\nabla \times \boldsymbol{H}^i = \varepsilon_0 \frac{\partial}{\partial t} \boldsymbol{E}^i \tag{4}$$

Let us use Eqs. (1) to (4) and note that the problem is a two-dimensional one with the TM wave (E_z^i, $E_z^s \neq 0$ and H_z^i, $H_z^s = 0$). Then, Maxwell's equations are rewritten as

$$-\mu_0 \frac{\partial}{\partial t} H_x^s = \frac{\partial}{\partial y} E_z^s \tag{5}$$

$$-\mu_0 \frac{\partial}{\partial t} H_y^s = -\frac{\partial}{\partial x} E_z^s \tag{6}$$

$$\varepsilon \frac{\partial}{\partial t} E_z^s + \sigma E_z^s = \frac{\partial}{\partial x} H_y^s - \frac{\partial}{\partial y} H_x^s - \left[(\varepsilon - \varepsilon_0) \frac{\partial}{\partial t} E_z^i + \sigma \cdot E_z^i \right] \tag{7}$$

If the central differences of Eqs. (5) to (7) are taken [only Eq. (7) is given],

$$\begin{aligned} E_z^{s,n+1}(i,j) &= \frac{\varepsilon - \sigma \Delta t/2}{\varepsilon + \sigma \Delta t/2} E_z^{s,n} + \frac{\Delta t}{\varepsilon + \sigma \Delta t/2} \\ &\times \frac{H_y^{s,n+(1/2)}\left(i + \frac{1}{2}\right) - H_y^{s,n+(1/2)}\left(i - \frac{1}{2}\right)}{\Delta x} \\ &- \frac{\Delta t}{\varepsilon + \sigma \Delta t/2} \\ &\times \frac{H_x^{s,n+(1/2)}\left(j + \frac{1}{2}\right) - H_x^{s,n+(1/2)}\left(j - \frac{1}{2}\right)}{\Delta y} \\ &- \frac{(\varepsilon - \varepsilon_0)\Delta t}{\varepsilon + \sigma \Delta t/2} \frac{\partial}{\partial t} E_z^{i,n+(1/2)} \\ &- \frac{\sigma \Delta t}{\varepsilon + \sigma \Delta t/2} E_z^{i,n+(1/2)} \end{aligned}$$

By using the internal electric field $E_z^s + E_z^i$ ($= E_z^M$) of the human body computed using the difference equations derived here, the local SAR and the whole body average SAR are derived from

$$\text{Local SAR} = \frac{\sigma |E_z^M|^2}{\zeta} \tag{8}$$

$$\text{Average SAR} = \int_s (\text{Local SAR}) ds/S \tag{9}$$

where S is the cross-sectional area of the cylindrical body model, ζ is the density of the body, and σ is the conductivity of the body. In this analysis, an elliptical shape with its long axis in the y direction is shown as the analyzed shape of the shield material as an example (Fig. 1). In future analyses, an elliptical shape with its long axis in the x direction and with partial coverage (in the range indicated by θ in Fig. 1) rather than whole coverage around the body will be used. Further, in addition to the cylindrical model, different human models, such as a homogeneous elliptical cylinder model, will be studied. When a conductive film is used as the shield material, a protective film (PET film) several millimeters thick formed for protection of the conductive layer is not taken into account in the analysis because the frequency used is between 900 and 1900 MHz [3].

3. Analysis Shape

In the present analysis, the permittivity ε_{r1} and the conductivity σ as the electrical constants of the human model are two-thirds of the electrical constants of the muscle often used [6], as shown in Fig. 1, while the permeability is the free space value μ_0. The body is an infinite circular cylinder with a radius of 0.1128 m. The density ζ of the human model is analyzed under the assumption that the height and weight are 175 cm and 70 kg, the values of average adults. The power density P of the incident plane wave is P = 1 mW/cm^2. The cell widths dx and dy in the FDTD method are $dx = dy = 2.0$ mm in the case without shield material and $dx = dy = 1.0$ mm with shield. The equivalent resistivity R_s of the thin conductive film is obtained by the following effective approximation [4] with its thickness d [m] and conductivity σ_s:
In this model, each parameter for the analysis is varied as

$$R_s = \frac{1}{\sigma_s d} \tag{10}$$

follows. (1) The frequency (f) of the incident plane wave is 900, 1500, 1800, and 1900 MHz, including the resonance region and the hot spot region. (2) The distance (GAP) between the conductive film and the human model is between 10 and 70 mm in consideration of the actual use condition. (3) The surface resistivity (R_s) of the conductive film is 40 and 80 Ω · □, taking into account the manufacturable range [7].

4. Analysis Results

4.1. Whole body average SAR

In order to confirm effectiveness of the FDTD method in the analysis of the absorbed power for the human model, the analysis results of the average SAR without the conductive film are presented in Fig. 2. "First MUR" indicates the results obtained by the FDTD method with MUR's first-order absorbing boundary condition. "M.E." indicates the results using the modal expansion method [9]. "Number of cells" on the horizontal axis indicates the number of cells along each axis. The numbers of cells in the x and y directions are the same.

From this figure, it is seen that as the number of cells is increased, the results approach those of the average SAR computed by the modal expansion method. For example, in the case of the number of cells of 600 × 600, the error of the analysis results by the FDTD method versus the modal expansion method is 0.31, –0.50, and –0.66% at 900, 1500, and 1900 MHz. Thus, the effect of reflection from each absorbing boundary decreases as the number of cells, or the analysis volume, is increased, so that the effectiveness of the present analysis using the FDTD method is confirmed.

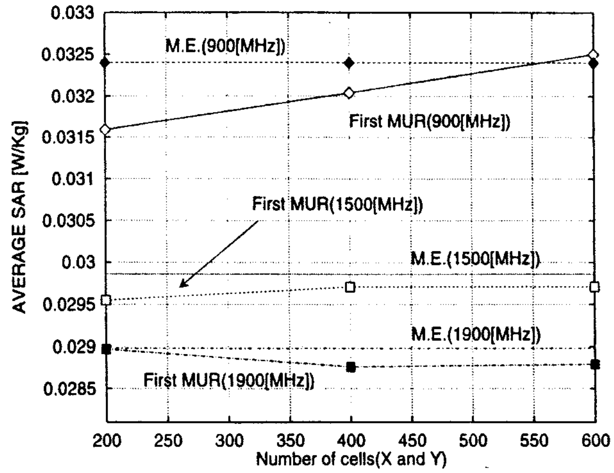

Fig. 2. Average SAR in the case of no shielding.

Next, the circularly shaped conductive film is placed in front of the human body in a concentric manner. In the case of surface resistivity R_s of 40 and 80 Ω · □, the analysis results are shown in Fig. 3 for the average SAR when the distance between the shield material and the human body is varied. Here, the analysis results are for the case where

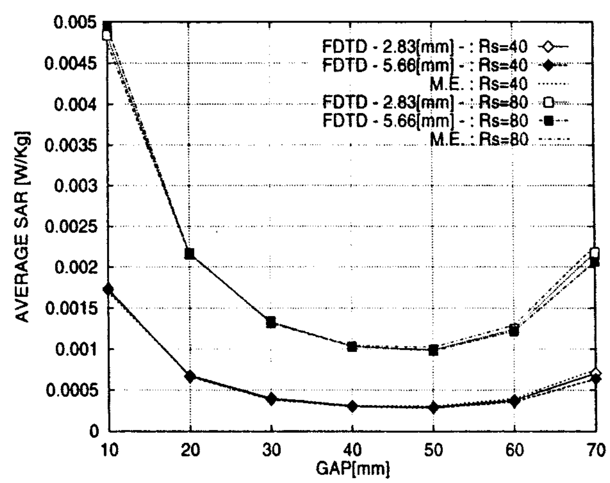

Fig. 3. Average SAR with distance between the shield and the human model.

the frequency of the incident plane wave is 1800 MHz. In what follows, all of the analyses with the shield material are carried out at this frequency. In this figure, the thickness values d = 2.83 and 5.66 mm of the shield material are arbitrarily chosen. The conductivity σ_s obtained by substituting this thickness value and the surface resistivity into the approximate equation (10) is then substituted into each cell comprising the shield to form a resistive film. "FDTD" and "M.E." indicate the results obtained by the FDTD method and the modal expansion method.

From this figure, it is seen that the average SAR can be reduced by decreasing the surface resistivity R_s of the conductive film and that the average SAR changes substantially depending on the distance between the human model and the shield material. The results using the FDTD method and those using the modal expansion method agree well with respect to the variations of the GAP and the surface resistivity. Further, agreement tends to increase as the thickness (d) of the shield material is made smaller. Hence, the effectiveness of the analysis by the present FDTD method using the approximate equation (10) of the equivalent surface resistivity is confirmed.

Figure 4 shows the analysis results of the average SAR when the conductive film in front of the human model is given an elliptical shape. In this figure, the eccentricity (e) is varied from 1.0 to 1.2. "(y direction)" indicates a shield shape longer in the y direction (incident direction), and "(x direction)" indicates a shape longer in the x direction (perpendicular to the incident direction). "FDTD," "P.M.," and "M.E." indicate analysis based on the FDTD method, point matching method, and modal expansion method [8], respectively.

From this figure, it is seen that the analysis results by the FDTD method and the point matching results agree well in the case of distance for which no resonance phenomena (in which the energy is concentrated due to multiple reflection between the shield material and a human model with a high permittivity [2]) occur. There are some discrepancies at the distance causing a resonance phenomenon. It is believed that the error in the approximation (10) taking into consideration the thickness (d) of the shield material became large at the distance for the resonance. Such errors are considered to be resolved by making the cell widths (dx and dy) finer and by expressing the thickness (d) smaller as discussed for Fig. 3. Variations of the average SAR caused by the change of distance between the shield and the human model at various parts of the model can be confirmed. Especially in the elliptical shape of the shield material longer in the incident direction, the resonance is seen near distance of 70 and 60 mm when the ellipticity is 1.1 and 1.2.

Figure 5 shows the analysis results of the average SAR in the case where the shield range of the conductive film placed in front is varied as θ = 120°, 180°, and 360°. "θ = 120°" indicates the shield material size is one-third (120° in front with 60° on both sides of the y-axis in Fig. 1), "θ = 180°" is one-half (180° with 90° on both sides of the y-axis in Fig. 1), and "θ = 360°" is the case in which the human body is wrapped by the shield material.

From this figure, it is seen that the shield effect decreases as the range of shielding is reduced. As the distance between the shield material and the human body increases, the shield effect can still be obtained even if the shield range is decreased. When there is a resonance, the

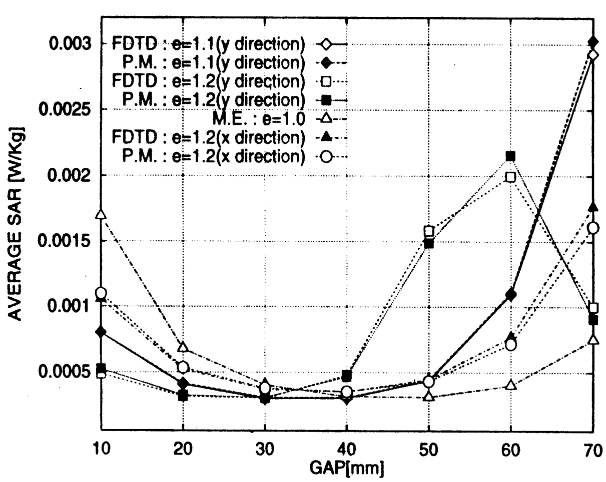

Fig. 4. Average SAR in the case of an oval shield.

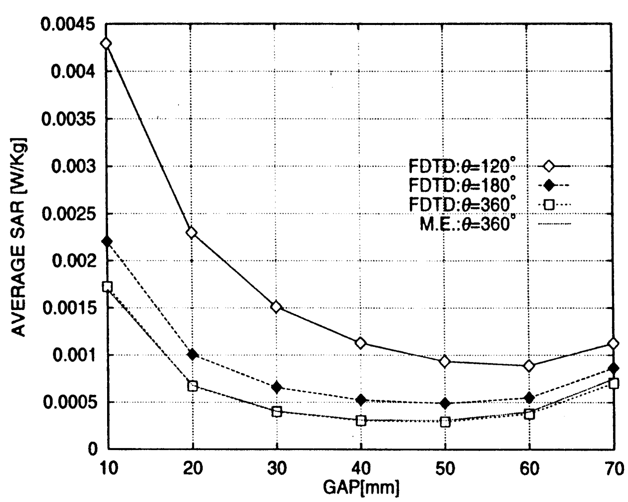

Fig. 5. Average SAR with varying shielding area.

energy concentrated in front of the body where the electromagnetic wave is incident can be effectively shielded. Therefore, the shield effect can still be obtained even with a smaller range of shielding material cover.

Finally, Fig. 6 shows the analysis results of the average SAR when an elliptically shaped conductive film is placed in front of the homogeneous elliptical human body model. In this figure, the ellipticity (e) is varied from 1.0 to 1.2. "Shield" indicates the case in which only the shape of the shield material is varied in an elliptical shape. On the other hand, "Human and Shield" indicates the case in which the shapes of both the human model and the shield material are varied. The results in this figure are for the elliptical shape longer in the x direction (normal to the incident direction), assuming that the electromagnetic wave is incident from the frontal direction of the human body.

From this figure, it is confirmed that an even larger shielding effect can be obtained than the cylindrical model even with the same surface resistivity.

4.2. Local SAR

The analysis results of the local SAR obtained by the FDTD method in the case without conductive film in a cylindrical human model are shown in Fig. 7. As an example of the resonance of the average SAR, the local SAR is shown in Fig. 8 when the surface resistivity R_s is 40 $\Omega \cdot \square$ and the distance between the shield and the human body is 70 mm. Further, as an example of the shield effect, Fig. 9 shows the local SAR in the case of surface resistivity R_s of 40 $\Omega \cdot \square$ and distance of 20 mm between the conductive film and the human model. In these figures, the shield range is

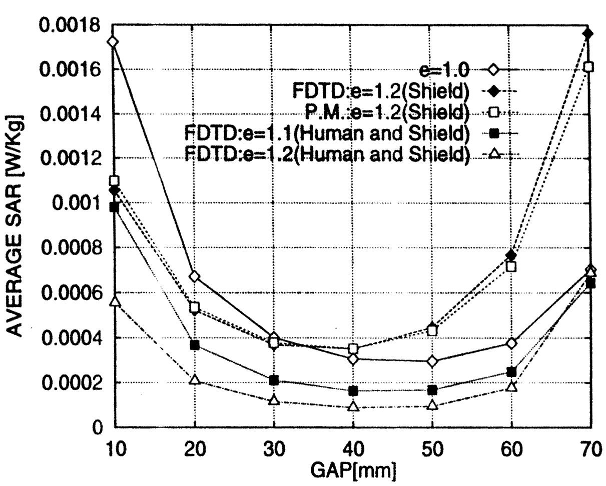

Fig. 6. Average SAR in the case of an oval shield and elliptical human model.

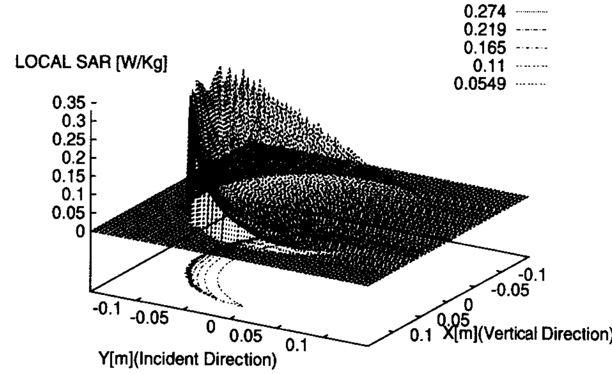

Fig. 7. Local SAR in the case of no shielding.

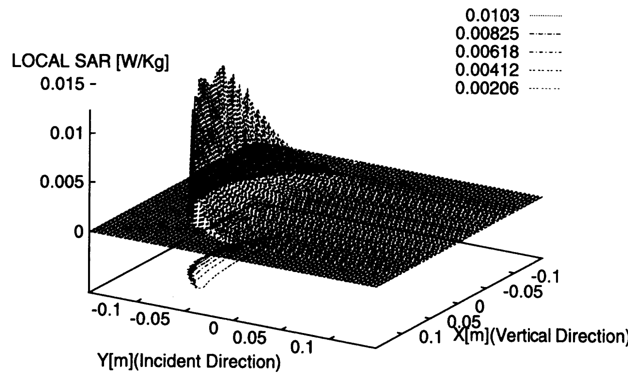

Fig. 8. A sample of local SAR in the case of resonance.

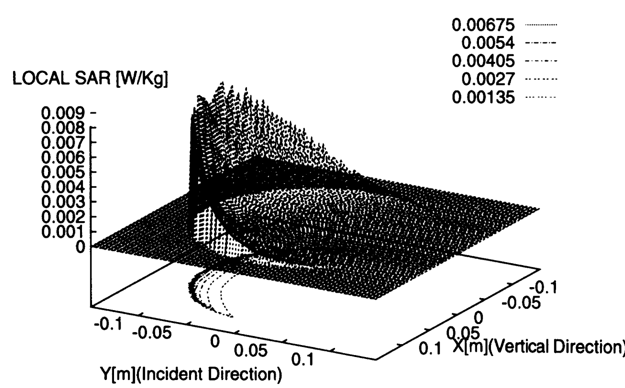

Fig. 9. A sample of local SAR in the case of shielding effect.

360°, and the incident electromagnetic wave frequency is 1800 MHz. The direction of incidence is from the left to the right in each figure.

From these results, it is seen that there is a large local SAR in the front of the human body model where the electromagnetic wave is incident. In the case where the distance between the shield and the human body is 20 mm (in Fig. 9), a rather high local SAR is spreading in a wide area in the front part of the human model. When the resonance previously discussed appears (in Fig. 8), the energy is concentrated in the front part of the human model so that a large local SAR appears.

5. Conclusions

In this article, from the viewpoint of human protection from electromagnetic waves, a thin, light, and flexible conductive film was selected as a shielding material. The average SAR and the local SAR were analyzed for the variations of shape of the conductive film and of the human body.

The following results were obtained.

(1) By means of the analysis method using the approximate equation (10) for the equivalent surface resistivity to the FDTD method, we have demonstrated the possibility of a shielding effect when a thin conductive film is placed in front of the human body model as a shielding material.

(2) By means of this analysis method, we have shown that an analysis is possible in the cases where a conductive film is placed partially in front of the body and where an elliptical shape shield is used. These cases have not been analyzed previously.

(3) In the analysis of the shield effect,

(a) it is shown quantitatively that the average SAR can be reduced by decreasing the surface resistivity R_s of the conductive film,

(b) it is found that there are cases in which the resonance occurs depending on the distance between the conductive film and the body and the shield effect can be degraded (so that the SAR is increased),

(c) the quantitative relationship is shown between the shield effect and the shield range of the conductive film placed partially in front of the model, and

(d) the variations of the shield effect for an elliptical human body model that is more realistic as a model are quantitatively presented.

As future topics, an analysis in a three-dimensional model and an experimental investigation with the conductive film are conceivable.

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