Applicability Evaluation of the Field Reconstruction Method Based on Boundary Integral Equations for Practical Uses

Rasyidah Hanan Mohd Baharin\textsuperscript{1a)}, Michiyoshi Nakamura\textsuperscript{1}, Toru Uno\textsuperscript{1}, and Takuji Arima\textsuperscript{1}

\textsuperscript{1} Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology, Naka-cho, Koganei-shi, Tokyo 184-8588, Japan
\textsuperscript{a)} rh.baharin@gmail.com

Abstract: Authors have proposed the internal electric field reconstruction method of dielectric objects based on the boundary integral equation and the method of moments’ implementation for the purpose of noninvasively estimating a specific absorption rate (SAR) in a human phantom. The validity of the method has been confirmed numerically and experimentally using simple-shaped convex dielectric objects with a very small loss. This paper assessed this method in three of more practical situations which is a concave model, a high-loss dielectric box, both for SAR estimation in the complex human phantoms, and also in a metallic enclosure with a window for the electromagnetic interference (EMI) applications. It is demonstrated numerically and experimentally that the electric field can be well reconstructed for all three situations without any methodological modifications. Hence, this method is expected to inherently possess high applicability for practical objects with a complicated geometrical shape in SAR estimation, and also for the EMI problems that includes the electric field reconstruction using the surrounding field data.

Keywords: SAR, phantom, shield box, electromagnetic field, inverse problems, boundary integral equation

Classification: Electromagnetic compatibility (EMC)

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1 Introduction

Electromagnetic radiation (EMR) and exposure from wireless terminals for industrial-use and/or personal-use are a major cause of concern to the human health. The Specific Absorption Rate (SAR) was established as a safety standard and it must be strictly adhered by any devices emitting electromagnetic (EM) waves. A noninvasive electric field (E-field) reconstruction method based on boundary integral equations was proposed in order to overcome the drawbacks of the conventional SAR estimation method using insertion of electric field probe to the liquid phantom. The reconstruction method enables conversion of receiving probe’s measurement data to EM surface currents of the transmitting device under test (DUT) and E-field in a target body. A convex-shaped model which is a flat cuboid and sphere with small loss was considered in the study. Although the validity of the effectiveness have been successfully proven, in reality, the real human body is not such a simple structure and contains highly lossy parts. Hence in this paper, the assessment of reconstruction method in a concave shape and a highly lossy medium are considered in order to demonstrate the calculation performance in complex human phantom that more closely mimics the human body.

Meanwhile, an EM shielding is a form of safeguarding against external EMR and to prevent signal leakage from a circuit or a set of electrical equipments. Though a complete-covering by a perfect conducting box is an ideal manner, slots or apertures are almost certainly equipped, with one of the surfaces for pulling in the power line and/or air vents for heat dissipation. For this reason, the metallic enclosure with window is often used for modelling these EMI investigations. The noninvasive reconstruction approach for the E-field on the aperture may be beneficial for this purpose. The inverse method aforementioned essentially applies the reconstruction of electric field distribution, therefore, it would also be suitable for this problem. For this reason, the reconstruction method was also extended to EMI shielding application without any methodological modifications to demonstrate an entirely independent problem, in which a conducting box with window enclosing a dipole antenna was selected. For all three cases, the

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results calculated are compared to forward solution of method of moments (MoM) as the reference while the shield box case has additional validation with experimental results in an anechoic chamber.

2 Overview of reconstruction method

In this section, we will briefly review the reconstruction method for the benefit of the reader. This method was based on Poggio-Miller-Chang-Harrington-Wu-Tsai (PMCHWT) formulation described in [1] and extended by Omi et al. by applying probe correction [2]. It relates the radiated field observed at probe, \( E_{\text{ext}} \), to equivalent currents \( J_{\text{DUT}} \) on the surface of DUT, \( S_{\text{DUT}} \) to currents \( J_{\text{sc}} \) and \( M_{\text{sc}} \) on the surface of the scatterer, \( S_{\text{sc}} \) given as

\[
E_{\text{ext}} = -L^{k_0}_{S_{\text{sc}}} (\eta_0 J_{\text{DUT}}) - L^{k_0}_{S_{\text{sc}}} (\eta_0 J_{\text{sc}}) + K^{k_0}_{S_{\text{sc}}} (M_{\text{sc}})
\]

(1)

\( L \): Electric surface current integral;  \( K \): Magnetic surface current integral  
\( \eta_n \): Intrinsic wave impedance;  \( k_n \): Wave number;  
\( n = 0 \) (free space, F.S.) and \( n = 1 \) (scatterer).

It is important to note here that the first main part represents direct propagation from DUT to the probe, while the second main part which is the expressions on the curly brackets equals to the scattered surface currents, \( [J_{\text{sc}} \ M_{\text{sc}}]^T \). The current distribution on \( J_{\text{DUT}} \) was discretized in a classical MoM manner using RWG triangle as a basis function. The linear equation is then solved in least-square sense to obtain \( J_{\text{sc}} \) and \( M_{\text{sc}} \). In a least-square approximation, the better solver converges, the smaller the residual error, indicating accurate results have been achieved in general. But, the solver needs longer computational time or converges to the local minimum for the inadequate residual value. We set the residual as \( 10^{-3} \) or less in order for the reconstruction results to be acceptable. After Eq. (1) is solved and we obtain \( J_{\text{sc}} \) and \( M_{\text{sc}} \), applying boundary equivalence theorem allows us to obtain the solution of internal \( E \) of scatterer by a simple additive inverse operation as follows.

\[
E_{\text{in}} = L^{k_1}_{S_{\text{sc}}} (\eta_1 J_{\text{sc}}) - K^{k_1}_{S_{\text{sc}}} (M_{\text{sc}})
\]

(2)

Omi has confirmed the validity of the method using a lossless convex phantom and a phantom having small loss tangent. However, the phantom used in practical dosimetry might be concave, convex, or combinations of both. In addition, the phantom is also realistically very lossy. These are not discussed in detail previously. Besides that, we also found that the method is plausible to apply in the case where \( S_{\text{sc}} \) is an electrical conducting surface such as
metallic shield box, as the main formulations will not be directly affected. As such, the next section discusses our findings in deploying the original method to these three new cases.

3 Assessment of method to extended applications

This section discusses the deployment of reconstruction method to extended cases. The three subsections are arranged in the same manner. Firstly, the simulation parameters and model are presented. Following that, comparisons of numerical results and forward solution of MoM from FEKO will be shown. For the results, the figures labelled as 'FEKO (MoM)' indicates the $|E|$ results are taken directly from the simulator FEKO, while 'Reconst. Method' means that the $|E|$ are numerically calculated from $E_{\text{ext}}$, using Eq. (1)—(2). For numerical implementations, the value of $E_{\text{ext}}$ is extracted from FEKO. Additional validation using experimental data is included in subsection 3.

The rest of parameters are listed as follows. The operating frequency is 2.5 GHz. The transmitter (Tx) or DUT is a $\lambda/2$ dipole (6cm) antenna located in $x-y$ plane and the receiver (Rx) or probe is assumed as a Hertzian dipole, except in measurement procedure. A hemisphere sampling for the field data is deployed with the Tx placed 5$\lambda$ (60cm) from Rx with angular sampling interval of $\Delta \theta = \Delta \phi = 5^\circ$. The reconstruction surfaces are known and are specified using GMSH software [6].

3.1 Concave dielectric models

A geometry shaped like a flipped letter "U" with permittivity $\varepsilon_r = 4$ is selected as a simple concave dielectric as shown in Fig. 1(a). The model is a 6cm $\times$ 6cm $\times$ 6cm cube, but with a cavity of 6cm $\times$ 3cm $\times$ 3cm on one side. This roughly represents a deep-grooved region of the human body such as the area between neck and shoulder, or between fingers. The distribution of E-field strength in $x-y$ plane and on an observation line shown by dashed line in the color map are shown in Fig. 1(b) and Fig. 1(c), respectively. F.S. here means free space of vacuum. It can be seen that the relatively large error points appear just on the boundary. The matrices for the least square calculations here becomes singular due to the singularity of Green’s function contained in the operators $L$ and $K$ [7] in Eq.(1), therefore, the large difference from the reference MoM data is expected. These points have no actual importance and should be discarded, because these values are mathematically integrable or determinable and can be given separately from the equivalent EM currents by means of Love’s equivalence theorem [2]. However, these singular points are remained in the figures just for the reader’s reference.

It is found that the reconstructed results agree extremely well with that of MoM’s forward solution except for near the boundary between the vacuum cavity and the scatterer. By excluding the boundary between the F.S. and scatterer, the error between reference and reconstructed shown in Fig. 1(b) was estimated to be less than 3.3%.
3.2 Lossy cube

The geometry of a cube with dimensions $6\text{cm} \times 6\text{cm} \times 6\text{cm}$ as the lossy scatterer is shown in Fig. 2(a) where its conductivity is $\sigma = 3$. Fig. 2(b) and Fig. 2(c) are $|\mathbf{E}|$ distribution plotted in the similar way to the previous subsection, respectively. The results also agree very well with the two lines almost completely overlapping each other, except at a few singular points near the boundary. By excluding these singular points, the error between reference and reconstructed shown in Fig. 2(b) was estimated to be less than 1.2%. The magnitude of the wave decreases exponentially as it propagates inside the cube, hence, we can see that most of the power is deposited in the lossy medium, resulting in very low level of $|\mathbf{E}|$ in this region.
3.3 Conducting enclosure with window

A hollowed copper-plate (Cu) box of dimensions 20cm × 20cm × 20cm with a 10cm × 10cm window for the simulation and experiment is shown in Fig. 3(a). The thickness of the copper-plate is 3mm. The DUT is a 6cm dipole antenna and is located in the center of the enclosure.

For the measurement, two dipoles namely Schwarzbeck UHA 9125D-144 (6cm) and UHA 9125D-143 (4.8cm) are set as Tx and Rx, respectively. Antenna factor needed for the E-field measurements was separately determined by a preliminary experiment. A photograph of the experimental setup is shown in Fig. 3(b). The |E| distribution in the window and on the observation line through the color map’s center are shown in Fig. 3(c) and Fig. 3(d), respectively. In these figures, the reconstruction results which are labelled as ‘Reconst. Method - Sim.’ are the same context as that of Fig. 1(b) — 1(c) and Fig. 2(b) — 2(c), which means the |E| is reconstructed from $E_{\text{ext}}$ of simulator, FEKO. Meanwhile,
'Reconst. Method - Meas.' means that the $\mathbf{E}_{\text{ext}}$ are collected from Rx as shown in Fig. 3(b). From the figures, it can be seen that the reference data (label: FEKO (MoM)) agree well with the numerical calculations, when the $\mathbf{E}_{\text{ext}}$ are taken from simulator environment (label: Reconst. Method - Sim). Reconstruction from experimental data (label: Reconst. Method - Meas), however, shows unsymmetrical results of field distribution. By excluding the singular points, the error percentage of Fig. 3(c) of reconstruction from simulation data and experimental, compared to the reference, was estimated to be less than 5.6% and 28%, respectively. At first glance, the error in measurement environment may seem very high, but a cut through the observation line as shown in Fig. 3(d) indicates rather satisfactory agreement. However, the mechanical alignment of the rotating table and an unexpected cable scattering may have contributed to the unsymmetrical results. Notwithstanding that our experimental setup contains these unavoidable errors, we can conclude that the simulation results agree acceptably well with the experiment, and that the effectiveness and significance for application in EMI problem were experimentally demonstrated.

4 Conclusion

In this letter, we have examined the applicability and expandability of reconstruction method in the concave dielectric model and lossy box for noninvasively estimating SAR in human phantom, and also the metallic enclosure with a window for EMI applications. It was demonstrated numerically and experimentally that the method provides accurate results in all three cases, and hence, possesses high applicability to the selected practical uses without any methodological modifications. However, only the estimation at points very close to the boundary includes relatively large error since the observation point located exactly on the boundary becomes a singular point of integral which is removable using the Love’s equivalence theorem. Although these points are not possible to be discarded automatically during the computational procedure, the singularity can be easily removed by using the equivalence theorem separately, and then, obtaining the respective electromagnetic field values are feasible from the equivalent surface currents. By exclusion of these singular points, all reconstruction results using simulation environment achieved very high accuracy. The experimental results supported this outcome, however, the susceptibility of this method to measurement error in experimental environment should be addressed by improving the scanning method, and we plan to study this in the future.
Fig. 3. Conducting enclosure with window.

(a) Simulation and experiment model.

(b) Photograph of experiment setup.

(c) $|E|$ distribution at the window.

(d) $|E|$ at observation line.