

Development of Inverse Problem Analysis System in Electromagnetics

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ABSTRACT

An inverse problem analysis system for electromagnetic fields, for use in the field of brain-machine interfaces (BMI), has been developed. In the conventional technique, a spherical approximation of the human head is used for the calculation of the electromagnetic field in the brain. The spherical approximation presents the issues that the shape and electromagnetic properties of the human head cannot be considered in the calculations, and that the currents normal to the surface of the sphere cannot be detected. In order to address these issues, we used the boundary element method (BEM) as a numerical method, to calculate the electromagnetic field, in addition to developing the mesh model and mesh generation method that were essential to the calculations. We employed a minimum-variance spatial filter as the method for inverse problems and applied a sub-grid technique to minimize the increase in calculation time of the numerical method. We verified the effectiveness of the method using a numerical simulation problem to reconstruct the hypothetical electric current sources in the brain. The results showed that the system was able to analyze inverse problems with consideration of the shape and electromagnetic properties of the tissues of the human head.

1. Introduction

Research is underway world-wide to develop interface technologies to operate devices by thought alone. Interface technologies of this type are called brain-machine interfaces (BMI)⁽¹⁾. If BMI technologies make it possible for people to operate information devices, home electronic devices and even cars without touching them, it will not simply increase operability, but will also increase the freedom of device design and modes of use. In addition, it would help expand the potential for people with physical disabilities to operate devices around them, and could thus be expected to contribute to the field of welfare. At present, research on basic technologies for BMI is proceeding at a number of research institutes. Because BMI necessitates devices to be operated by specific brain activity, technologies to sense that brain activity are an important element. It is unrealistic to implant sensors in the brain in order to sense brain activity, and it is necessary to develop non-invasive measurement technologies able to detect brain activity and inverse problem analysis technologies to make it possible to calculate the position of the current in the brain on the basis of the measurement data.

Near infrared spectroscopy (NIRS) and functional magnetic resonance imaging (fMRI) are non-invasive

technologies able to measure brain activity. These technologies are able to detect the biological phenomenon of increased blood flow in active areas of the brain. NIRS is a detection method that uses infrared light, while fMRI uses strong magnetic fields. Because there is a several-second time lag between brain activity and increased blood flow, both methods present a delay in detection. Furthermore, NIRS presents the difficulty in detecting changes in blood flow in the deep regions of the brain. Other methods are also available that do not measure secondary biological phenomena such as blood flow, but that directly measure current in the brain as an electromagnetic phenomenon. Methods that detect brain waves (through changes in the electric potential of the skin of the scalp) or brain magnetism (through changes in the magnetic field around the head) are representative, and are termed electroencephalography (EEG) and magnetoencephalography (MEG), respectively. The detection lag for both methods is in the sub-millisecond range, and they are both able to detect activity in deep areas of the brain. They can therefore be expected to find application in BMI.

2. Issues of Conventional Technologies

The position of the current in the brain can be

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determined by solving an inverse problem with the electric signals obtained by EEG or the magnetic signals obtained by MEG as input conditions. A system that determines the position of the current in the brain using MEG has already been developed, and is being used in a variety of medical research. The following steps are used to determine the position of the current.

- (1) The magnetic field produced by brain activity is measured using magnetic field sensors.
- (2) Calculation points are set for the current source (on a grid).
- (3) A coefficient termed the lead field is calculated for each grid.
- (4) An inverse problem is solved based on the sensor signal and the lead field, and the position of the current is determined.
- (5) The determined position of the current is displayed on the grids as an image.

The lead field is a coefficient that expresses the relationship between the current sources and the sensor signals. It expresses the electric field and the magnetic field that a unitary current source creates at the position of the sensor. The lead field is determined by electromagnetic calculations from the shape, electromagnetic properties, the position of the current in human tissues, and from the position and orientation of the sensors. Standard lead field calculation uses a spherical approximation for the brain shape. When the brain is assumed as a perfect sphere with a homogeneous medium and the current density vector $\mathbf{J}$, is localized at position $\mathbf{r}_0$, the magnetic field $\mathbf{H}$ at position $\mathbf{r}$, can be expressed by Eq. (1)⁽²⁾.

$$\mathbf{H}(\mathbf{r}) = \frac{1}{4\pi A^2} (A\mathbf{J} \times \mathbf{r}_0 - \mathbf{J} \times \mathbf{r}_0 \cdot \mathbf{r} \nabla A) \quad (1)$$

$$A = |\mathbf{r} - \mathbf{r}_0| (|\mathbf{r}| |\mathbf{r} - \mathbf{r}_0| + |\mathbf{r}|^2 - \mathbf{r}_0 \cdot \mathbf{r})$$

If spherical approximation is used in the lead field calculations, two issues arise. The first issue is that it is not possible to consider the shape or electromagnetic properties of the tissues of the human head. The broken lines in Fig. 1 show a spherical approximation superimposed on the brain in a human head. It is clear that the brain is not a perfect sphere, and that there exist large gaps between the lower

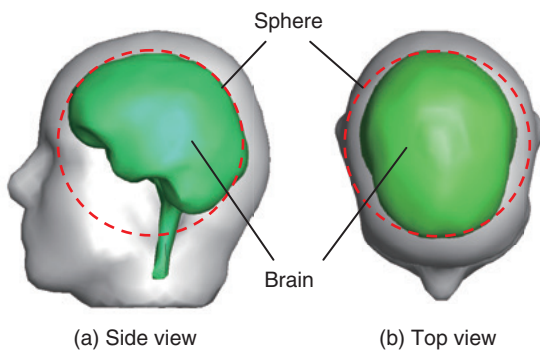


Fig. 1 Human head and sphere

section and sides of the sphere and the brain. The shape of the brain differs for each test subject, and these differences cannot be considered when using a spherical approximation. In addition, there is no term for electromagnetic properties in Eq. (1), meaning that electromagnetic properties cannot be considered.

The second issue is the occurrence of a dead zone. When approximating the brain to a sphere, the calculated value of the magnetic field produced by the electric current normal to the spherical surface is 0. This is caused by the symmetry of the sphere. Because of the various convexities, concavities and asymmetries of the real human subjects, the generated magnetic field is not 0. The currents cannot be calculated with spherical approximation and lead to the calculated current distribution differing from the actual one.

In order to address these issues, a numerical analysis is adopted instead of spherical approximation. The numerical analysis calculates lead fields by solving Maxwell's equations considering shape and electromagnetic properties. As numerical analysis necessitated a mesh model, we developed a human head model and a mesh generation method. We also developed a grid generation method to generate calculation points for the current sources. A minimum-variance spatial filter was applied as the inverse problem analysis method, and, in order to minimize the increase in calculation time due to the numerical method, a sub-grid technique was employed. An inverse problem analysis system for electromagnetic fields was developed using these technologies. Chapter 3 will discuss the technologies making up the system in greater detail. Chapter 4 will consider the testing of the system, and Chapter 5 will provide the conclusions reached.

3. Element Technologies of Inverse Problem Analysis System for Electromagnetic Fields

3.1. Mesh and Mesh Generation Method for Human Model

Because a BEM was employed in the calculation of the lead fields, as will be discussed below, a human surface mesh model was necessary. The head was divided into layers based on the differences in electric conductivity of tissues, and a mesh was generated for the surface of each tissue layer. Figure 2 shows an example of a four-layer model of the human head generated by this system. The tissues of the human head are represented by four mesh surfaces. From the outermost layer, these are the skin, the skull, the cerebrospinal fluid, and the brain. The conductivity of the tissues adjacent to the inside and the outside is imparted to each layer of mesh as data on electromagnetic properties.

The mesh should satisfy the following conditions.

- (1) The size and shape of the elements should be as uniform as possible.
- (2) The model should display good shape reproducibility.
- (3) Mesh generation should be rapid.

We developed a new mesh generation method because there were no appropriate methods and tools that would satisfy the above conditions. Mesh generation has two steps: generation of uniform elements and deformation of mesh into a human head. First, a mesh was generated with a sphere as the base surface in order to verify the uniformity of the elements. The surfaces of regular polyhedral elements were subdivided recursively, and projected onto the surface of a circumsphere in order to generate a spherical mesh with the necessary number of elements. Because of this subdivision of the surfaces of regular polyhedrons and projection onto a spherical surface, the elements are basically uniform with minimal distortion, and the process of mesh generation is rapid. The number of elements is controlled by varying the number and frequency of the subdivisions. The subdivision points for the elements are calculated using Eq. (2). Here, $\mathbf{r}_a$ and $\mathbf{r}_b$ are coordinate vectors of both ends of the edge, and $\mathbf{r}_c$ is the coordinate vector of the point at which the edge is internally divided by p:q and projected onto the circumsphere. In all cases the origin point is the center of the sphere.

$$\mathbf{r}_c = \frac{|\mathbf{r}_a|}{|q\mathbf{r}_a + p\mathbf{r}_b|} (q\mathbf{r}_a + p\mathbf{r}_b) \quad (2)$$

Figure 3 shows an example of subdivision of a mesh in which the edge is divided equally twice. From the left, the figure shows an icosahedron mesh, the mesh after one subdivision, and the mesh after two subdivisions.

When the human head is imaged using MRI, a cross-sectional image of varying shades is obtained in response

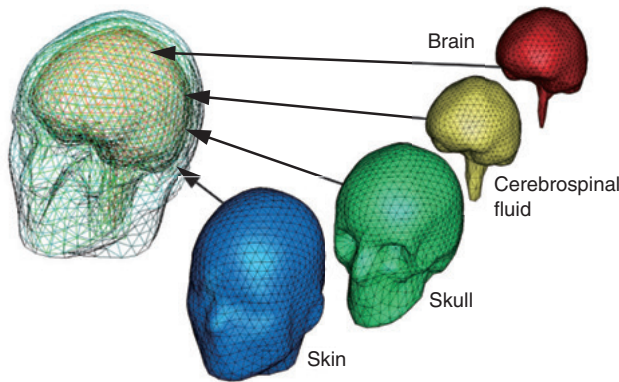


Fig. 2 Mesh model of human head with four shells

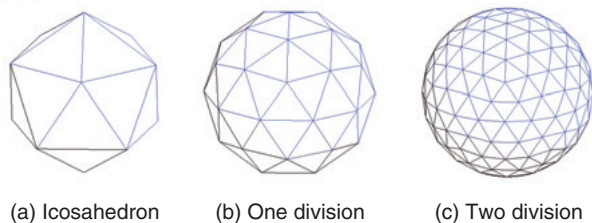


Fig. 3 Mesh refinement

to the physical properties of the tissues. The shape of the head can be reproduced three-dimensionally by layering these cross-sectional images. As shown in Fig. 4(a), a surface mesh can be generated by positioning this three-dimensional MRI image data of the head on a spherical mesh so as to enroll it, and projecting the mesh onto the tissue surface from the MRI data. The tissue for which the mesh is generated can be selected by varying the intensity of the MRI data on which it is projected.

The projection operation is performed by translating the nodes of the spherical mesh onto the points expressed by Eq. (3).

$$\mathbf{r}_p = \mathbf{r}_s + \gamma \frac{\mathbf{v} \cdot (\mathbf{r}_m - \mathbf{r}_s)}{\mathbf{v} \cdot \mathbf{v}} \mathbf{v} \quad (3)$$

$\mathbf{v}$ is the inward normal vector of the spherical mesh, $\mathbf{r}_s$ is the vector of the node of the spherical mesh, $\mathbf{r}_m$ is the closest MRI data point vector to $\mathbf{r}_s$ in the vicinity of the direction of $\mathbf{v}$, γ is a positive real number of 1 or less and is a coefficient expressing the projection ratio, and $\mathbf{r}_p$ is the vector of the projected point. When the concavity and convexity of the tissue surface is comparatively minimal, a mesh deformed into the tissue shape can be obtained using one projection with $\gamma=1$. When there is significant concavity and convexity of the tissue surface, a number smaller than 1 is used for γ , and, following deformation of the spherical mesh to make it slightly resemble the concave and convex shapes of the tissue, smoothing is applied to correct distortion in the mesh. This operation is repeated until the mesh shape sufficiently resembles the concave and convex tissue surface, and is finally projected onto the tissue surface with $\gamma=1$. We used the Taubin method⁽²⁾ for smoothing. Figure 4(b) shows an example of the generation of a mesh model of brain tissue including the spinal cord generated by four stages of deformation and projection.

3.2. Method of Generation of Grid for Inverse Problem

A grid in the brain is generated in order to calculate the distribution of the current source. First, a rectangular

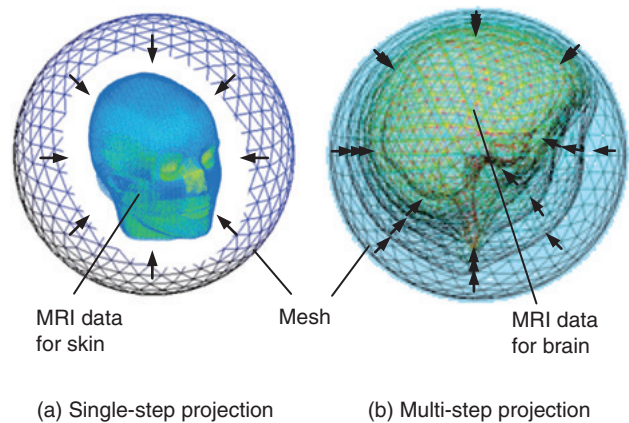


Fig. 4 Projection of spherical mesh

parallelepiped domain that includes the brain is covered by a grid, and the grid outside the brain is deleted. The values of the solid angles are used in judging interior and exterior. The solid angles of the grid points in relation to the brain surface mesh are expressed by Eq. (4). Here, $\mathbf{r}_{i1}$, $\mathbf{r}_{i2}$, and $\mathbf{r}_{i3}$ are position vectors in relation to the grid point of the i^{th} triangular element node, and N is the number of elements in the brain surface mesh.

$$\Omega = 2 \sum_{i=1}^N \tan^{-1} \frac{\det(\mathbf{r}_{i1}, \mathbf{r}_{i2}, \mathbf{r}_{i3})}{|\mathbf{r}_{i1}| |\mathbf{r}_{i2}| |\mathbf{r}_{i3}| + |\mathbf{r}_{i1}| (\mathbf{r}_{i2} \cdot \mathbf{r}_{i3}) + |\mathbf{r}_{i2}| (\mathbf{r}_{i3} \cdot \mathbf{r}_{i1}) + |\mathbf{r}_{i3}| (\mathbf{r}_{i1} \cdot \mathbf{r}_{i2})} \quad (4)$$

When the grid point is in the brain surface mesh, the solid angle is 4π , when the grid point is on the boundary, it is 2π , and when the grid point is outside, it is 0. Figure 5(a) shows a grid covering a rectangular parallelepiped domain containing the brain. Figure 5(b) shows results with the grid outside the brain and the brain surface grid removed.

3.3. Calculation of Lead Field

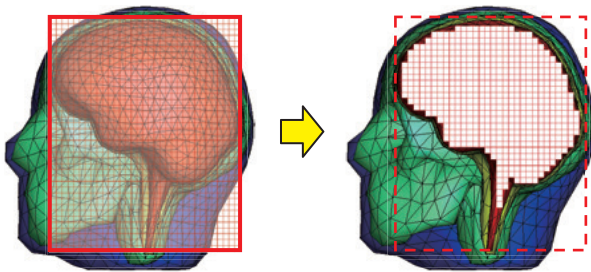
A variety of numerical analyses that are able to consider the shape and electromagnetic properties of the human head are available, including the finite difference method, the finite element method, and the boundary element method (BEM). We adopted a BEM for its calculation accuracy with minimal unknowns.

Equation (5) is Maxwell's equation, which expresses the electromagnetic field.

$$\begin{cases} \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, & \nabla \cdot \mathbf{D} = \rho \\ \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}, & \nabla \cdot \mathbf{B} = 0 \end{cases} \quad (5)$$

Here, $\mathbf{E}$, $\mathbf{H}$, $\mathbf{B}$, $\mathbf{D}$, $\mathbf{J}$, ρ and t are the electric field, the magnetic field, magnetic flux density, electric flux density, current density, charge density, and time, respectively. Terming the current density in the brain $\mathbf{J}^i$ and conductivity σ in order to consider current in the brain, the current density, $\mathbf{J}$, can be expressed by Eq. (6).

$$\mathbf{J} = \mathbf{J}^i + \sigma \mathbf{E} \quad (6)$$



(a) Full grid

(b) Trimmed grid

Fig. 5 Grid for inverse problem calculation

Taking the fact that current in the brain is a low-frequency signal of around several hundred Hz and applying a quasi-static approximation, Eqs. (5) and (6) can be reorganized to produce Eq. (7), which expresses the electromagnetic field of the current in the brain.

$$\nabla \times \mathbf{H} = \mathbf{J}^i - \sigma \nabla V \quad (7)$$

Here, V is electric potential. Using vector equations and Green's theorem, Eq. (7) is transformed into a surface integration equation. The surface integration equation used to determine electric potential is shown as Eq. (8). The surface integration equations used to determine the electromagnetic field are the simultaneous equations shown as Eqs. (8) and (9)⁽³⁾.

$$\frac{\alpha_k(\mathbf{r}) + \beta_k(\mathbf{r})}{2} V(\mathbf{r}) = \frac{1}{4\pi} \frac{\mathbf{J}^i(\mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}_s)}{|\mathbf{r} - \mathbf{r}_s|^3} - \sum_{j=1}^m \frac{\alpha_j - \beta_j}{4\pi} \int_{S_j} \frac{V(\mathbf{r}') \mathbf{n}(\mathbf{r}') \cdot (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dS_j \quad (8)$$

$$\mathbf{H}(\mathbf{r}) = \frac{1}{4\pi} \frac{\mathbf{J}^i(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}_s)}{|\mathbf{r} - \mathbf{r}_s|^3} - \frac{1}{4\pi} \sum_{j=1}^m (\alpha_j - \beta_j) \int_{S_j} \frac{V(\mathbf{r}') \mathbf{n}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dS_j \quad (9)$$

Here, $\mathbf{r}_s$ is the position vector of the current source, $\mathbf{n}(\mathbf{r})$ is the surface normal vector at $\mathbf{r}$, α is the conductivity of the internal contiguous tissue, β is the conductivity of the external contiguous tissue, S is the mesh faces, j and k are the numbers applied to the mesh faces, and m is the total number of mesh faces. A comparison of Eq. (1), in which the brain is approximated to a sphere, and Eq. (9) shows that it is the second term on the right-hand side of Eq. (9) that reflects the shape and electromagnetic properties of the tissue in the head.

The lead field can be determined by discretizing Eqs. (8) and (9), applying them to the human mesh and solving them using BEM. If the current at each grid point, $\mathbf{J}^i$, is assumed to be a unitary current, V determined from Eq. (8) becomes the lead field of an EEG. Similarly, $\mathbf{H}$ determined by coupling Eqs. (8) and (9) becomes the lead field of an MEG. Terms unrelated to the position of the current are stored in a coefficient matrix and LU decomposition is applied, and the solution is found through reverse substitution and forward substitution for each current source.

3.4. Method for Inverse Problem

Using the lead field, $\mathbf{L}(\mathbf{r})$, the relationship between the strength of the current source at position $\mathbf{r}$, $s(\mathbf{r}, t)$ and measurement data, $\mathbf{b}(t)$, can be expressed by Eq. (10).

$$\mathbf{b}(t) = \int \mathbf{L}(\mathbf{r}) s(\mathbf{r}, t) d\mathbf{r} \quad (10)$$

Here, measurement data refers to measurement data

for the electric potential, V , in the case of EEG and measurement data for the electromagnetic field, $\mathbf{H}$, in the case of MEG. Using a minimum-variance spatial filter, a technique that is often applied in EEG and MEG inverse problems, the strength of the current source is reconstructed via Eq. (11).

$$\hat{s}(\mathbf{r}, t) = \mathbf{W}^T(\mathbf{r})\mathbf{b}(t) \quad (11)$$

Here, $\hat{\cdot}$ is used as a superscript to distinguish $\hat{s}(\mathbf{r}, t)$ from true $s(\mathbf{r}, t)$. $\mathbf{W}(\mathbf{r})$ is a weight vector for reconstruction. $\mathbf{W}(\mathbf{r})$ is determined so as to minimize the effect on current sources in other positions when the sensitivity to the current source in position $\mathbf{r}$ is 1. It is found by minimizing Eq. (13) based on the constraint conditions given by Eq. (12).

$$\mathbf{W}^T(\mathbf{r})\mathbf{L}(\mathbf{r}) = 1 \quad (12)$$

$$\mathbf{W}^T(\mathbf{r})\langle \mathbf{b}(t)\mathbf{b}^T(t) \rangle \mathbf{W}(\mathbf{r}) \quad (13)$$

Here, $\langle \cdot \rangle$ represents the time average. $\mathbf{W}(\mathbf{r})$ is expressed by Eq. (14).

$$\mathbf{W}(\mathbf{r}) = \frac{\mathbf{R}^{-1}\mathbf{L}(\mathbf{r})}{\mathbf{L}^T(\mathbf{r})\mathbf{R}^{-1}\mathbf{L}(\mathbf{r})}, \quad \mathbf{R} = \langle \mathbf{b}(t)\mathbf{b}^T(t) \rangle \quad (14)$$

Using $\mathbf{W}(\mathbf{r})$, the current source is reconstructed from Eq. (11)⁽⁴⁾.

3.5. Application of Sub-grid Technique to Inverse Problems

The refinement of the grid of inverse problems is useful for the enhancement of the position accuracy of the solution. On the other hand, the calculation time increases due to the increased number of calculation points. In order to address the issue, we applied the sub-grid technique used in forward problems to inverse problems. The sub-grid technique is able to limit the refinement to necessary areas only. First, inverse problems were solved for a coarse grid in order to determine the positions of high current source strength. Following this, the areas of the grid contiguous to these positions were finely subdivided using sub-grids of a pitch of 1/2, and inverse problems were solved in the areas in which the sub-grid had been used in order to determine the positions of high current source strength in greater detail. When this operation is performed a predetermined number of repetitions, the positions of high current source strength can be determined with good accuracy. The grid points in the areas in which the sub-grids were generated at which the first-order differentials of the current source strength in all directions are positive are then determined. Following this, a fixed number of points are determined in order of current source strength. Figure 6 shows a flow chart of the application of the sub-grid technique to inverse problems. Here, N_{max} is the maximum number of iterations of the grid.

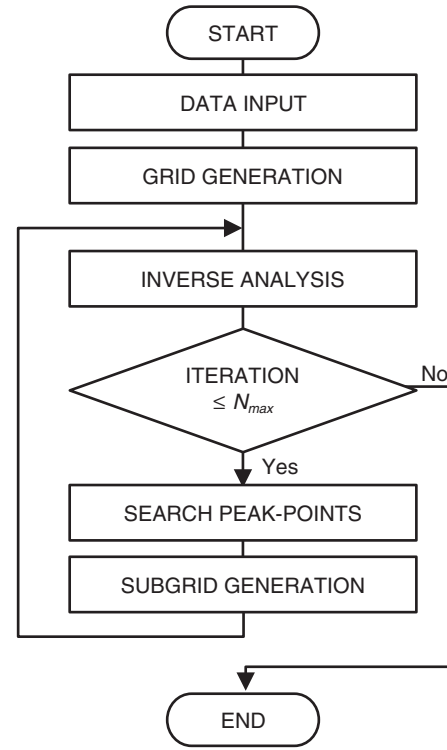


Fig. 6 Flowchart of inverse problem analysis with sub-grids

4. Verification of Effectiveness of System

In order to verify the effectiveness of the system, generating currents freely in an actual human brain is ideal but effectively impossible. We therefore adopted a numerical simulation for the verification⁽⁵⁾. The simulation assumed a 210-channel MEG sensor in the vicinity of the head, and three current sources with differing coordinates, directions and waveforms in the brain. The electromagnetic field at the position of the sensor was calculated in advance as a forward problem. This value was regarded as the sensor signal, and inverse problems were solved in order to verify the reconstruction of the current sources. Figure 7 shows

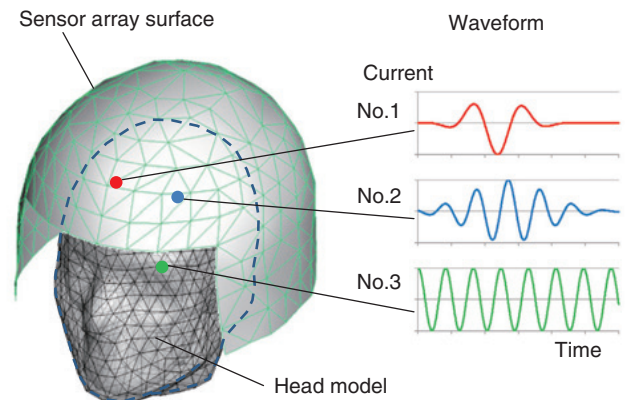


Fig. 7 Model of inverse problem analysis

Table 1 Position and direction of sources

Source No.	Position [mm]	Direction
1	(5, -17.5, 57.5)	(1, 0, 0)
2	(5, 20, 57.5)	(1, 1, 0)
3	(5, 12.5, 20)	(0, 1, 1)

Table 2 Waveform of sources

Source No.	Wave form
1	$\exp\left(-\left(\frac{t-0.47}{1.2/5.9}\right)^2\right) \sin\left(\frac{2\pi \cdot 3.8 \cdot (t-0.556)}{1.2}\right)$
2	$\exp\left(-\left(\frac{t-0.54}{1.2/3.8}\right)^2\right) \sin\left(\frac{2\pi \cdot 6.3 \cdot (t-0.492)}{1.2}\right)$
3	$\sin\left(\frac{2\pi \cdot 7.3 \cdot (t-0.455)}{1.2}\right)$

the head model, the sensor array surface, and the current sources. The electromagnetic sensor was positioned at the nodal points of the sensor array surface mesh. The head model was the four-layer head model discussed in Chapter 3. Table 1 shows the position and direction of the current sources, and Table 2 shows their waveforms. The front, left and top of the head from the perspective of the test subject were the positive directions of the x, y and z axes, respectively, and the center of gravity of the head was the origin point of the coordinates.

Calculations for analysis of inverse problems were compared using the following two types of grids. In each case, the minimum grid pitch was 2.5 mm.

- (1) Analysis of inverse problems using a grid with a pitch of 2.5 mm (Without using sub-grids)
- (2) Analysis of inverse problems using a grid with a pitch of 10 mm (Two iterations for the sub-grids)

Figure 8 shows the two types of grid. The grids in the head mesh are shown as cross-sections.

Table 3 shows the calculation results. Both of the grids were able to reconstruct all three current sources in their simulated positions. The application of sub-grids has made it possible to reconstitute current sources using a coarse grid with a pitch of 10 mm with the same level of accuracy as a grid with a pitch of 2.5 mm. In addition, the use of the

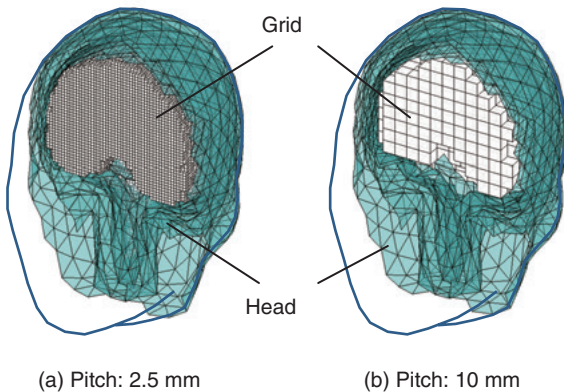


Fig. 8 Grids for inverse problem analysis

Table 3 Results of reconstruction of the sources

Pitch of grid [mm]	2.5	10 (+Sub-grid)
Position [mm]	No.1	(-5, -17.5, 57.5)
	No.2	(-5, 20, 57.5)
	No.3	(5, 12.5, 20)
Calculation time [sec]	4101	190

rough grid reduces calculation time to approximately 1/22, with calculations being completed in 190 seconds, against 4,101 seconds for the 2.5 mm grid.

Figure 9 shows the calculation results. The red points show the points at which current density is high, indicating that the three current sources have been reconstructed. Figure 9(b) shows a 2.5-mm sub-grid being automatically generated around the current source.

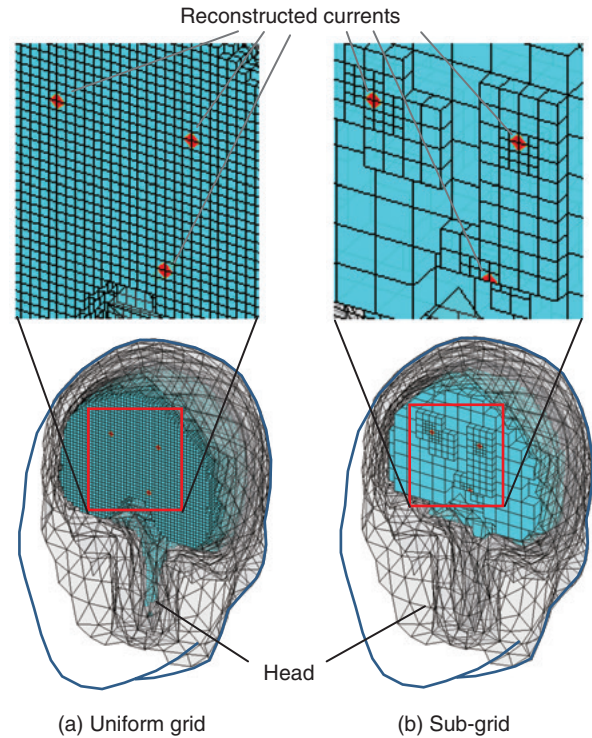


Fig. 9 Reconstructed currents in brain

5. Conclusion

An inverse problem analysis system for electromagnetic fields that reconstructs current sources in the brain has been developed. In order to address the issues of the conventional calculation method, which approximates the head to a sphere, this project applied a method in which the lead field was calculated using BEM, and developed the human head mesh model, mesh generation method, and generation method for the inverse problem calculation grid. In addition, a minimum-variance spatial filter was

employed as the method for inverse problems and a sub-grid technique was applied, increasing the speed of calculations. The effectiveness of the system was verified using a numerical simulation that reconstructed currents in the brain. When the sub-grid technique was applied to a grid with a pitch of 10 mm, the same level of position accuracy in the solution was obtained as a grid with a pitch of 2.5 mm at approximately 1/22 the calculation time. The developed system is able to reconstruct current sources with consideration of the shape and electromagnetic properties of a human head. The system applies the sub-grid technique to the solution of inverse problems for magnetic fields, but it is applicable to inverse problems in a variety of fields, including fluid analysis, structural analysis, and acoustic analysis. The extension of the system to a wide range of fields is scheduled for the future.

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