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LOCALIZATION OF LOW-FREQUENCY SOURCE CURRENT DISTRIBUTIONS

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1. Introduction

Electromagnetic (EM) noise field distributions measured externally around electrical and electronic equipment have been used for localization and identification of the noise sources inside the equipment. For high frequencies (more than hundreds of MHz), the EM sources at finite distances have been localized by applying the techniques such as MUSIC [1], SPM [2], and holographic imaging [3], to the EM fields observed by a sensor array. On the other hand, at very low frequencies, the problem of localizing near-field EM sources has been solved for example in bioelectromagnetic inversion problems, such as the MUSIC localization of the current dipoles within human brains [4]. By applying the MUSIC algorithm [4][5] to the magnetic field distributions measured with an array of magnetic vector sensors placed around low-frequency (less than MHz) magnetic dipoles, we have estimated the 3-d locations and orientations of multiple incoherent [6] and/or coherent [7] *small* current loop sources. For *larger* current loops whose loop sizes are not negligible, we have extended the MUSIC algorithm to estimate their sizes as well as their locations and orientations [8]. However, the extended algorithm has assumed the shape of the source current loops simply as hexagonal. In this study, we try to estimate the shape of the source current distributions, by applying the GVSPM (Generalized Vector Sampled Pattern Matching) method [9], combined with the MUSIC algorithm.

2. MUSIC localization of current loop sources

Suppose there are N_S incoherent magnetic dipoles (*small* current loops) placed at locations $\boldsymbol{l}_{S,i}$ with the orientations of the dipole axes $\boldsymbol{d}_{S,i}$ $(i = 1, 2, \cdots, N_S)$. The magnetic field distribution generated from these source dipoles is measured by N_A magnetic sensors. Here the number of sensors N_A is assumed to be larger than the number of sources N_S. With the eigenanalysis of the covariance matrix calculated from the measured magnetic field distribution, we have N_S large (signal) eigenvalues and $N_A - N_S$ small (noise) eigenvalues, from which we can estimate the number of sources. Then we determine the source locations and orientations, by searching for the local maxima of the MUSIC cost function P_{music} defined as

$$P_{music}(\boldsymbol{l}, \boldsymbol{d}) = \frac{\left\| \boldsymbol{a}(\boldsymbol{l}, \boldsymbol{d}) \right\|^2}{\left\| \boldsymbol{E}_N^H \boldsymbol{a}(\boldsymbol{l}, \boldsymbol{d}) \right\|^2}, \qquad (1)$$

where ^{H} means the Hermitian conjugate. Here $\boldsymbol{a}(\boldsymbol{l}, \boldsymbol{d})$ is the “steering vector,” which represents the magnetic fields to be observed by the sensors when a source is located at $\boldsymbol{l}$ with orientation $\boldsymbol{d}$. The noise subspace $\boldsymbol{E}_N$ spanned by the corresponding noise eigenvectors should be orthogonal to the steering vector for each of the true sources, $\boldsymbol{a}_i\left(\boldsymbol{l}_{S,i}, \boldsymbol{d}_{S,i}\right)$, where (1) takes a local maximum. The MUSIC cost function (1) can be modified as a function of only the location $\boldsymbol{l}$, when we decompose the steering vector $\boldsymbol{a}$ into the elementary steering vectors for the x, y, and z-directional dipole sources. In that case (1) takes the local maximum at each of true source dipole locations, where we can extract the information on the dipole orientations [6]. The maximization of the MUSIC cost

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functions can be performed efficiently by a non gradient-based method, such as the Nelder-Mead simplex [10].

When two or more dipoles have correlated time-series of waveforms (i.e., coherent sources), the conventional MUSIC algorithm fails to localize either of the dipoles because the coherent sources give only a single signal eigenvalue. By adopting the spatio-temporal "independent topography" model used in the biomagnetic localization of the synchronous current dipoles within human brains [11], we can search for the coherent dipole sources corresponding to the single eigenvalue. The MUSIC cost function is modified so as to be scanned over their locations simultaneously (i.e., a multiple dipole search). Even when there exist incoherent and coherent dipoles, we can effectively localize both of them with the RAP (recursively applied and projected) MUSIC algorithm [12].

The effectiveness of the MUSIC localization of magnetic dipole sources for incoherent [6] and coherent [7] dipoles has been demonstrated by numerical simulations and by experiments. For the dipoles within the distance of several meters from the sensor array, the estimation error is less than a few millimeters for location and less than 1 degree for orientation in numerical simulations. Such an estimation error tends to become larger in experiments, because of limitation in accurate experimental setup of the locations and orientations of sensors and sources.

For the *large* current loop sources whose loop sizes are not negligible compared with the distance between the sensor array and the sources, we have to modify the steering vectors to represent the magnetic field distributions generated by finite-size current loops. In this case it becomes possible to estimate the sizes of the loops with the MUSIC algorithm, by scanning the additional "loop size" space, for the current loops modeled for example as circular. With numerical simulations and experiments, we have confirmed the applicability of such an algorithm to estimate the sizes as well as the locations and orientations of the finite-size current loop sources [8].

3. GVSPM localization of source current distributions

The above MUSIC algorithms are based on the pre-specified shape of the current loop sources, so that we are unable to know the actual current distributions on the loop sources. Nevertheless when applied for the case of *large* current loop sources with unknown current distributions, the MUSIC algorithm, even with the magnetic dipole model, gives approximately the center positions of the current loops and the directions normal to their loop planes. Here we apply the GVSPM method [9] to further estimate the current distributions on such localized "loop planes." The GVSPM method iteratively and effectively calculates the spatial distribution of source currents which generates the magnetic field distribution "approximately equal to" the actually measured one around the sources with the sensor array. The calculation procedure in this study is as follows. First we apply the MUSIC algorithm to localize the "loop plane" of each source, where usually we need the magnetic field distribution measured just at several points. Then we re-measure the more detailed magnetic field distribution (preferably at more than several tens of measurement points) on a plane for example parallel to the localized loop plane. Finally the GVSPM method is used to estimate the current distributions on the localized loop plane.

Figure 1 shows an experimental example of the estimated loop current distributions, where a square-shaped (70 cm on a side) current loop at 10 kHz is placed on the $x-z$ (vertical) plane, as shown by the solid lines on the figure. Figures 1(a) and 1(b) represent the current vectors and intensity contours, respectively, of the source current distribution estimated by the GVSPM method. The "x" mark indicating almost the center of the square loop in each figure is the source (assumed as a dipole) location first localized by the MUSIC algorithm applied to the magnetic vector fields measured only at three points around the loop. Here the GVSPM method has been applied to the magnetic vector field distribution which was re-measured at about 50 measurement points on a parallel plane 10 cm away from the "loop plane" first localized by the MUSIC algorithm. The size and shape of the current loop source are well reproduced here.

Figure 2 shows the estimated current distribution on an electric heater. Here there exists an almost square-shaped (about 20 cm on a side) current loop (the solid line) at 60 Hz in the lower part of the heater (the outline of which is plotted by the dashed line). In this case the GVSPM method has been applied to the magnetic field distributions re-measured on a plane 30 cm away from the source loop whose size is 20 cm. As seen in the figures the actual current routes are not well reproduced, which suggests that the magnetic field distribution measured at such a short distance comparable with the loop size would obscure the detailed shape of the estimated source loop.

4. Conclusion

We have applied the MUSIC algorithm to localize the multiple low-frequency current loop sources, and the GVSPM method to estimate the shape of the source current distribution on the *large* loops. With numerical simulations and experiments we have confirmed their applicability. We have been developing an experimental system to localize and visualize the low-frequency current loop sources on a computer screen in almost real-time, by superimposing them directly on the "real" video image of the sources. Figures 3(a) and 3(b) show examples of such visualization, where the current vector distributions estimated in the previous chapter are overlapped on actual images of the sources. Such a system would help us identify intuitively the EM noise sources during EMC tests of the electric and electronic equipment. To enhance the applicability of the developed algorithm we need to further refine it and improve the accuracy of the localization of the source current distributions.

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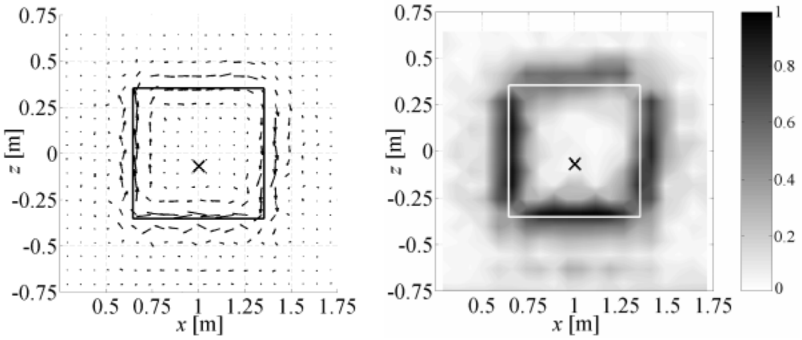
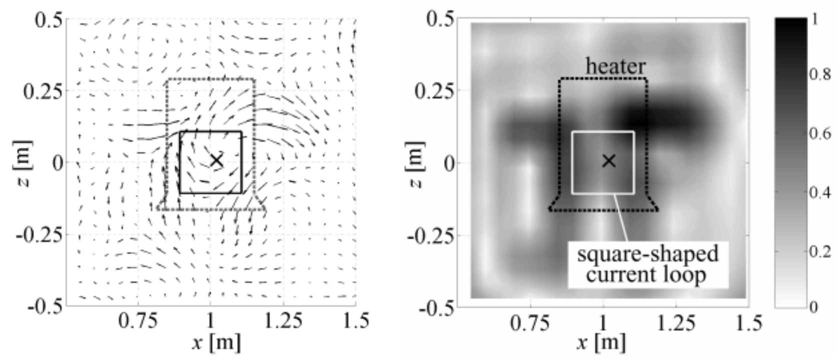


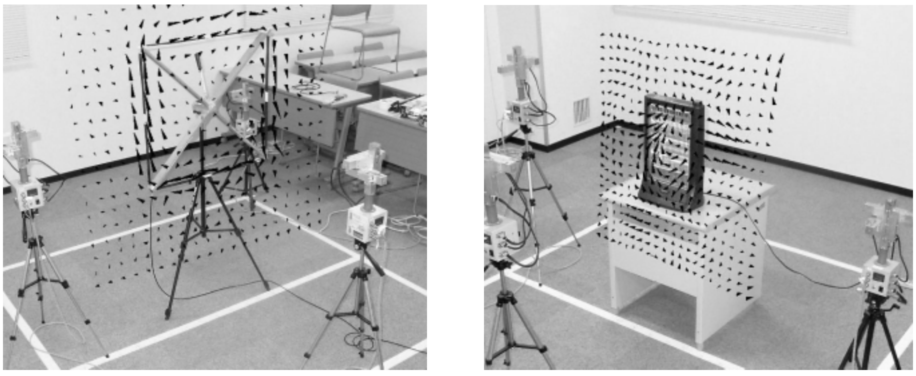
(a) current vectors (b) current intensities

Figure 1: Estimated current distribution on a square-shaped loop



(a) current vectors (b) current intensities

Figure 2: Estimated current distribution on an electric heater



(a) a square loop (b) an electric heater

Figure 3: Visualized images of source current distributions