Magnetic Flux Line Allocation Algorithm Using Magnetic Flux Line Existence Probability for Magnetic Flux Visualization

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The visualization of magnetic flux lines is one of the effective ways of observing a magnetic field. In the visualization of magnetic flux lines, it is necessary that the allocation of magnetic flux lines is determined according to the magnetic flux density. We have previously proposed two methods of determining the allocation of magnetic flux lines in 3-D space. However, both methods take a long computation time to determine the allocation of magnetic flux lines, because the Bubble System is utilized. For solving the problem, in this paper, we propose a method of shortly and appropriately allocating magnetic flux lines for depicting. In the proposed method, the magnetic flux line existence probability is employed. The proposed method takes much shorter time than the previously proposed methods. Moreover, it also takes a short time to redraw the magnetic flux lines when their number is changed.

***Index Terms*— Magnetic field, Magnetic flux line, Probability distribution, Visualization.**

I. Introduction

THE FINITE ELEMENT METHOD is widely used in electromagnetic field simulation. Since large-scale electromagnetic simulation is often performed with improvement of computer technology, the numerical data of simulation results have become huge. Hence, it is difficult to grasp a magnetic or electrical field only from the numerical data. The importance of visualizing the simulation results has increased. The visualization of magnetic flux lines is an effective way of understanding the magnetic field distribution in a whole 3-D space on a 2D display, because it enables us to observe or image the strength, orientation, and locus of magnetic field. It is, therefore, required to develop a practical method for magnetic flux line visualization. Magnetic flux lines have to be depicted according to the following rules:

(i) The density of magnetic flux lines enables us to perceive the strength of magnetic field, $|\boldsymbol{B}|$ (T).

(ii) The tangential direction of magnetic flux lines enables us to grasp the orientation of magnetic field.

We have previously proposed two magnetic flux line visualization methods [1], [2] satisfying the above-mentioned rules. The Bubble System [3] is utilized in both two methods. However, it takes a long computation time to simulate the bubbles' movement. In this paper, we propose a new allocation method of magnetic flux lines in order to shorten the computation time by using a magnetic flux line existence probability.

II. Allocation Method of Magnetic Flux Lines

A. Magnetic flux line existence probability

The number of magnetic flux lines N_{flux} passing through a plane is defined as

$$N_{\text{flux}} = BS, \tag{1}$$

where B and S are the magnitude of magnetic flux density perpendicular to the plane and the area of the plane, respectively. Hence, the number of magnetic flux lines N_{flux}^i passing through the tetrahedral element i is described as

$$N_{\text{flux}}^i = B_i S_i, \tag{2}$$

where B_i and S_i are the magnitude of magnetic flux density and the area of cutting-plane of the element i, respectively. As shown in Fig. 1, as a magnetic flux line penetrates a circle, the sum of N_{flux}^i of the elements in the circle has to be 1;

$$\sum_i N_{\text{flux}}^i = 1. \tag{3}$$

For visualization, when the magnetic flux density is too high/low, a user cannot effectively observe the magnetic field according to (3). Hence, in the proposed method, a parameter β how dense the magnetic flux lines are depicted is introduced in order to adjust the number of depicted magnetic flux lines. By using the parameter β, (2) is expressed as follows:

$$\alpha_i = \beta B_i S_i, \tag{4}$$

where α_i is the parameter termed "magnetic flux line existence (MFLE) probability" of the element i. When one magnetic flux line is depicted in a region with a total MFLE probability of 1, the allocation of magnetic flux lines satisfies the above-mentioned rules.

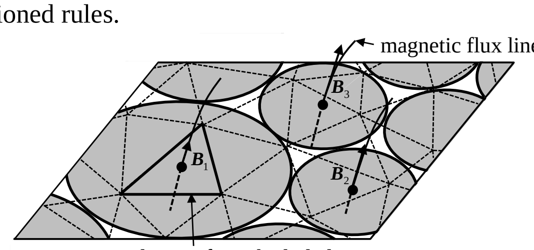


Fig. 1. One magnetic flux line penetrates one circle, whose area is inversely propotional to $\boldsymbol{B}_i$ (i = 1, 2, 3). The total of B_iS_i inside of the circle has to be 1.

B. Procedure of proposed method

As preprocessing, the magnetic flux density $\boldsymbol{B}$ and cross-sectional area S of every tetrahedral element are computed, and then the MFLE probability α is also calculated from (4).

The procedure is as follows:

Step 1: Select the element i with the largest value of $B_i\alpha_i$.

Step 2: Compute a magnetic flux line from the gravity point of the selected element i. The magnetic flux line is analytically computed from FEA result [4], [5]. The elements passed through by the magnetic flux line are defined as $E_{\mathrm{th},j}$ (j=1, 2, … , N_p), where N_p is the number of elements passed through by the magnetic flux line.

Step 3: Update the MFLE probability $\alpha_{E_{\mathrm{th},j},\mathrm{new}}$ of the elements $E_{\mathrm{th},j}$ as

$$\alpha_{E_{\mathrm{th},j},\mathrm{new}} = \alpha_{E_{\mathrm{th},j},\mathrm{old}} - \min(\alpha_{E_{\mathrm{th},j},\mathrm{old}}, 1.0). \quad (5)$$

Step 4: Calculate the required MFLE probability γ_{k+1} (γ_1 = 1.0) as

$$\gamma_{k+1} = \gamma_k - \sum\nolimits_{\lambda\in\boldsymbol{D}_k} \min(\alpha_{\lambda,\mathrm{old}}, \gamma_k/n_k) \quad (6)$$

with
$$n_k = |\boldsymbol{D}\Delta\boldsymbol{a}|, \quad (7)$$

where k is the step number of the MFLE probability decreasing process, $\boldsymbol{D}$ is the elements which have already updated the MFLE probability in (5) or (8) and $\boldsymbol{a}$ is the adjacent elements of $\boldsymbol{D}_{k-1}$. If γ_{k+1} is equal to 0.0 and j is equal to N_p, go to Step 6. If γ_{k+1} is equal to 0.0 and j is smaller than N_p, increase j by 1 and return to Step 3.

Step 5: Update the MFLE probability $\alpha_{ADJ_l,\mathrm{new}}$ of the adjacent elements ADJ_l ($\in \boldsymbol{D}\Delta\boldsymbol{a}$) as

$$\alpha_{ADJ_l,\mathrm{new}} = \alpha_{ADJ_l,\mathrm{old}} - \min(\alpha_{ADJ_l,\mathrm{old}}, \gamma_{k+1}/n_{k+1}) \quad (8)$$

Increase l by 1 and repeat Step 5 before l exceeds n_k, and then increase k by 1 and return to Step 4.

Step 6: If at least one element has larger MFLE probability than the arbitrary threshold ε, return to Step 1. Otherwise, all magnetic flux lines computed in Step 2 are visualized.

Fig. 2 shows the conceptual explanation that the MFLE probability decreases to 0 from Step 3 to Step 5. Fig. 3 shows the set of elements with a total MFLE probability of 1 for an arbitrary magnetic flux line.

III. Application

In order to confirm the validity of the proposed method, it is applied to a simple model consisting of two permanent magnets. Fig. 4 shows the visualization results of magnetic flux lines. From Fig. 4, the appropriate allocation of magnetic flux lines, satisfying the rules mentioned above is obtained. Table I shows the computation time of magnetic flux line

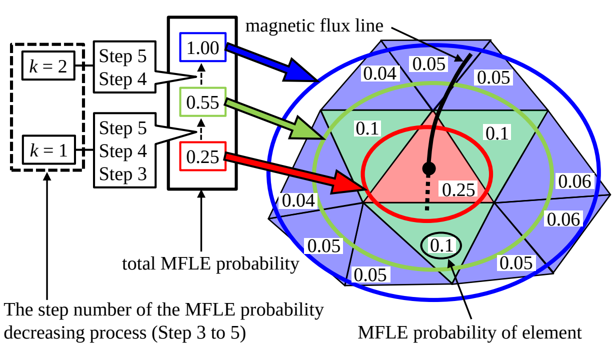


Fig. 2. MFLE probability decreasing process (from Step 3 to Step 5). In Step 3, the MFLE probability of red element ($E_{\mathrm{th},j}$) penetrated by a magnetic flux line decrease to 0. In Step 4, (= 1.0 – 0.25 = 0.75), and then in Step 5, the MFLE probability of the green elements are updated. Subsequently, the processes from Step 4 to Step 5 are repeated until $\gamma = 0$ (this process is colored by blue).

allocation by the proposed method and the previous one [2] for comparison. The proposed method takes a much shorter time than the previous method. Here, in the proposed method, it takes 12 s for computing $\boldsymbol{B}$ and S in the first drawing. However, these values can be reused for redrawing the magnetic flux lines as increasing/decreasing their number by adjusting the parameter β (in Figs. 4 (b) and (c)). Consequently, since the redrawing takes shorter time than the first drawing, a user can easily and instantly adjust the number of depicted magnetic flux lines.

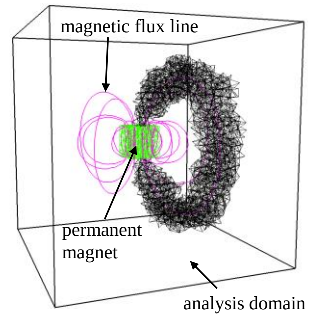
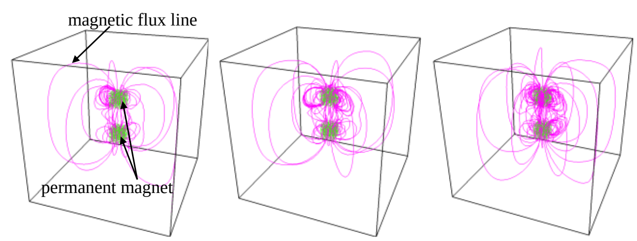


Fig. 3. All elements that have updated the MFLE probability in (5) or (8) for an arbitrary magnetic flux line are shown. These elements are not penetrated by any other magnetic flux lines.

TABLE I
Computation Time of Previous and Proposed Method

Method	# of flux lines	Computation time
Previous method [2]	50	A several ten hours
Previous method [2]	55	A several ten hours
Proposed method	43	13 s
Proposed method	55, 63	1 s



(a) first drawing (b) 55 flux lines (c) 63 flux lines

Fig. 4. Visualization results of magnetic flux lines by proposed method.

IV. References

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