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

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The visualization of magnetic flux lines is one of the most effective ways to intuitively grasp a magnetic field. The depiction of continuous and smooth magnetic flux lines according to the magnetic field is of paramount importance. Thus, it is important to adequately allocate the distribution of magnetic flux lines in the analyzed space. We have already proposed two methods of determining the allocation of magnetic flux lines in 3-D space. However, both methods exhibited a long computation time to determine the allocation of magnetic flux lines. For solving this problem, in this paper, we propose a new improved method for correct allocation of magnetic flux lines in 3-D space with modest computational cost. The main advantages of this method are shorter computation time, correct allocation of the magnetic flux lines, and especially short computation time for visualization of magnetic flux lines when changes in the number of depicted flux lines is requested.

***Index Terms*—Magnetic field, magnetic flux line, probability distribution, visualization.**

I. Introduction

Significant improvements in the computer technology enabled large-scale electromagnetic simulations which usually as a result generate huge amount of numerical data. Hence, it is difficult to grasp a magnetic or electrical field phenomenon only from the numerically obtained results. Thus, the importance of visualizing the simulation results is increasing. The visualization of magnetic flux lines is an effective way of intuitively 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, simultaneously.

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), and

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

The authors have already proposed several methods of analytically obtaining continuous and smooth magnetic flux lines from 3-D edge finite element analysis results [1]-[4]. These methods provide visualization of magnetic flux lines satisfying the rule (ii). However, they mostly failed to provide a way of selection and visualization of magnetic flux line allocation according to the rule (i).

Consequently, the authors proposed two other methods [5], [6] for magnetic flux line allocation utilizing the bubble system [7]-[9], which provide allocation of magnetic flux lines which satisfies the above-mentioned rule (i). However, the major drawback of these methods was their extremely long computation time (e.g., a several hours) to simulate the bubbles' movement.

In this paper, we propose a new method for proper allocation of the magnetic flux lines based on the computation of the magnetic flux line existence (MFLE) probability. The proposed method significantly shortens the computation time in comparison with the previously proposed methods [5], [6]. Once the MFLE probability is calculated for each finite element, it can be reused for any further visualization needs. This enables us to decrease the computation time for any further visualization of the magnetic flux lines regardless of the line density or the number of depicted flux lines in the 3-D space. Thus, the proposed method becomes highly suitable for any interactive visualization system.

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II. Method of Magnetic Flux Line Allocation

A. Concept of the Proposed Method

In the previously proposed method [6], a magnetic flux line was surrounded by a virtual tube whose cross-sectional radius was a function of the magnitude of magnetic flux density, as shown in Fig. 1(a). The computation of these virtual tubes was based on the bubble system. However, the process of simulation of the tube's movement always took a long computation time.

With the proposed method, to shorten the computation time, we propose a new method for adequately allocating magnetic flux lines within analyzed domain. Instead of virtual tubes with rounded cross sections, a set of elements that are not intersected by any other flux line, is constructed around a magnetic flux line to be depicted. To decide the size of a set of tetrahedral elements in accordance with the magnitude of magnetic flux density, we introduce a new calculation parameter called "*magnetic flux line existence* (*MFLE*) *probability.*" Hence, since it is easy to calculate the MFLE probability, the appropriate allocation of magnetic flux lines could be obtained much quicker than the previous methods [5], [6]. Fig. 1(b) shows a set of tetrahedral elements surrounding an arbitrary magnetic flux line in 3-D analysis domain.

B. MFLE Probability Calculation

The expected number of magnetic flux lines N_{flux} passing

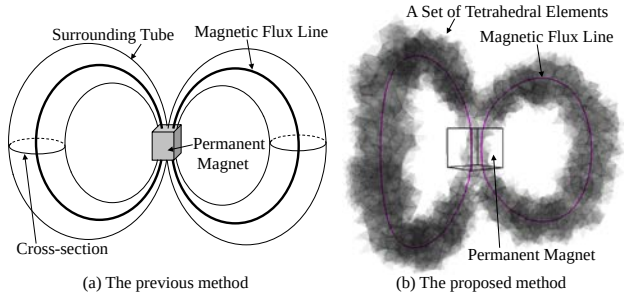


Fig. 1. (a) visualization of magnetic flux lines based on virtual tubes [6], and (b) magnetic flux lines surrounded by a set of tetrahedral elements in 3-D space.

through a plane S 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. As shown in Fig. 2, a magnetic flux line penetrates into a circle which corresponds to the cross section of virtual tube [6]. The total product B_cS_c inside one circle c has to be 1;

$$\int_c B_c \mathrm{d}S = 1 \ . \tag{2}$$

In the proposed method, to simplify the computation, a set of elements instead of a virtual tube is used. Hence, the number of magnetic flux lines N^i_{flux} passing through one tetrahedral element i could be calculated as follows:

$$N^i_{\text{flux}} = B_i S_i \ , \tag{3}$$

where B_i and S_i are the magnitude of magnetic flux density and the area of a cutting plane of the element i, respectively. Similarly to (2), the sum of N^i_{flux} of the elements has to be 1,

$$\sum_i N^i_{\text{flux}} = 1 \ . \tag{4}$$

For visualization purposes, when magnetic flux density is too high (or too low), a user cannot effectively grasp the magnetic field phenomenon only by means of depiction of the magnetic flux lines in accordance with (4). Hence, in the proposed method, an additional parameter β ($\beta > 0$) is introduced in order to adjust the number of depicted magnetic flux lines in correlation with the magnetic flux density. By using the parameter β, (4) could be rewritten as follows:

$$\alpha_i = \beta B_i S_i \ , \qquad \sum_i \alpha_i = \sum_i \beta B_i S_i = 1 \ , \tag{5}$$

where α_i is the parameter called "*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 fully satisfies the above-mentioned rule (i). Fig. 3 shows a set of elements with a total MFLE probability of 1, distinguished by different colors. Since this new set of elements is not a tube but a polygon, it is easier to compute (5), which results in very short computation time that exhibits our newly proposed calculation method.

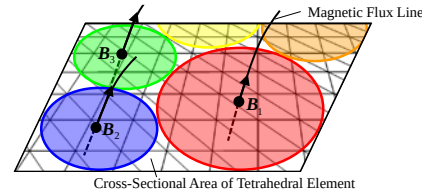


Fig. 2. One magnetic flux line penetrates one circle, whose area is inversely proportional to B_c (c = 1, 2, 3). The total value of B_cS_c inside of each circle has to be 1.

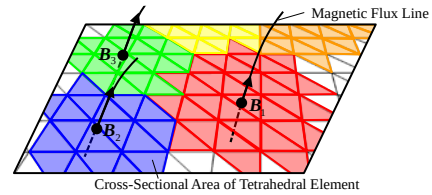


Fig. 3. The set of elements with a total MFLE probability of 1 are distinguished by different color.

C. Calculation Procedure

As preprocessing, the magnetic flux density $\boldsymbol{B}$ and the cross-sectional area S of every tetrahedral element are computed, where the cross section is perpendicular to $\boldsymbol{B}$ and contains the gravity point of the element, followed by calculation of the MFLE probability α for each element in accordance with (5). Next, the procedure continues as following:

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

Step 2: Compute a magnetic flux line placed at the gravity point of the selected element i. The magnetic flux line is analytically computed using FEA results [1], [2]. The elements through which this magnetic flux line passes are defined as e_j (j=1, 2, … , N_{p}), where N_{p} is the total number of elements passed through by this magnetic flux line.

Step 3: Update the MFLE probability $\alpha_{e_j,\text{new}}$ of element e_j as

$$\alpha_{e_j,\text{new}} = \alpha_{e_j,\text{old}} - \min(\alpha_{e_j,\text{old}}, 1.0) \ . \tag{6}$$

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

$$\gamma_{k+1} = \gamma_k - \sum_{\lambda \in \boldsymbol{D}_k} \min(\alpha_{\lambda,\text{old}}, \gamma_k / n_k) \tag{7}$$

$$\text{with } n_k = |\boldsymbol{D} \Delta \boldsymbol{a}| \ , \tag{8}$$

where k is the number of steps of the MFLE probability decreasing process, $\boldsymbol{D}$ is the elements which have already updated the MFLE probability in **Step 3** or **5**, and $\boldsymbol{a}$ is the adjacent elements of $\boldsymbol{D}_{k\text{-}1}$. When γ_{k+1} is equal to 0.0 and j is smaller than N_{p}, increase j by 1 and return to **Step 3**. When γ_{k+1} is equal to 0.0 and j is equal to N_{p}, go to **Step 6**.

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

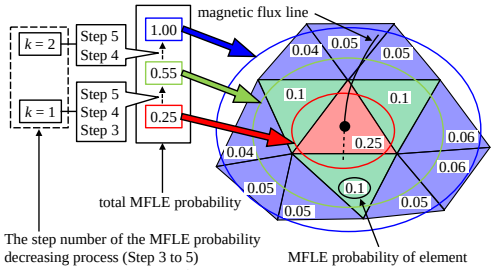


Fig. 4. Visual representation of MFLE probability decreasing process (from **Step 3** to **Step 5**). At **Step 3**, the MFLE probability of a red element (e_j) penetrated by a magnetic flux line decrease to 0. At Step 4, (γ = 1.0 – 0.25 = 0.75), and then in **Step 5**, the MFLE probability of the green elements are updated. Subsequently, the processes of **Step 4** to **Step 5** are repeated until γ = 0 (the blue-colored elements).

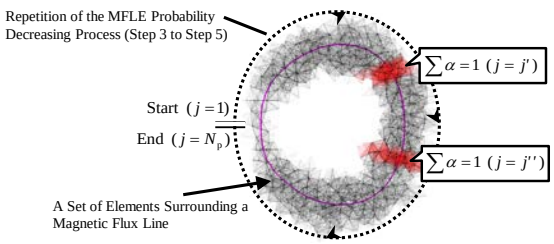


Fig. 5. Conceptual explanation of a process of allocation of a magnetic flux until it is surrounded by all elements.

$$\alpha_{ADJ\ i,\mathrm{new}} = \alpha_{ADJ\ i,\mathrm{old}} - \min(\alpha_{ADJ\ i,\mathrm{old}}, \gamma_{k+1}/n_{k+1}) . \tag{9}$$

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: When 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 depicted.

Fig. 4 shows the conceptual explanation how the MFLE probability decreases to 0 from **Step 3** to **Step 5**. As shown in Fig. 5, the processes of **Step 3** to **Step 5** are repeated for each magnetic flux line until j reaches N_p. Consequently, each magnetic flux line is surrounded by elements not penetrated by any other magnetic flux line (see Fig. 1(b)). After finishing all allocation processes, the following relation is satisfied:

$$\sum_i \sum_j \alpha_{ij} = \alpha_{\mathrm{all}} , \tag{10}$$

where α_{ij} and α_{all} are the MFLE probabilities of the element j passed through by the magnetic flux line i, and a total MFLE probability of all the elements in the whole analysis domain, respectively. Since (5) and (10) are satisfied, the allocation of all magnetic flux lines obtained by the proposed method is appropriately determined according to the rule (i).

D. *Changing the Number of Magnetic Flux Lines*

One function usually requested in any interactive visualization system is its ability to arbitrarily change the number of visualized magnetic flux lines. The previous method [6] exhibited same long time when changing the number of magnetic flux lines, as when the initial calculation of the magnetic flux lines, therefore, it was not suitable for interactive visualization.

In the proposed method, re-drawing of different number of magnetic flux lines takes only a few seconds, after their initial adequate allocation. Actually, when changing the number of the flux lines to be visualized only the parameter β in (5) has to be accordingly reset. However, since B_iS_i for all of the elements have already been calculated during the initial drawing, for re-drawing different number of flux lines the system needs only a very short computation time spent to recalculate the MFLE probability α_i based on the previously obtained B_iS_i. In this method, the calculation of B_iS_i takes ~96% of the total computation cost.

III. Applications

In order to confirm the validity of the proposed method, we present its application to two models: a simple single permanent magnet model, and a motor model. Using these two models, the following features of the proposed method are shown: 1) the adequate allocation of the magnetic flux lines, 2) the short computation time, 3) easy method for changing the number of flux lines, and 4) applicability of the method for magnetic flux lines visualization for more complex models.

A. *Simple Model Consisting of Single Permanent Magnet*

1) *Adequate Allocation of the Magnetic Flux Lines*

Fig. 6 shows the visualization of 80 magnetic flux lines allocated by the proposed method, and visualized in accordance with method presented in [1]. Fig. 7 shows the process of changes of the MFLE probability α distribution in the cross section of the permanent magnet until the allocation of all magnetic flux lines is determined. Comparison between flux lines presented in Fig. 6, it confirms that the proposed method provides the adequate allocation of magnetic flux lines, fully satisfying the rule (i).

2) *Decreasing of the Computation Time*

Table I shows the number of drawn magnetic flux lines and elements. Fig. 8 shows the computation time for the first and the second drawing in the old method and the newly proposed method, respectively. However, only the first-drawing

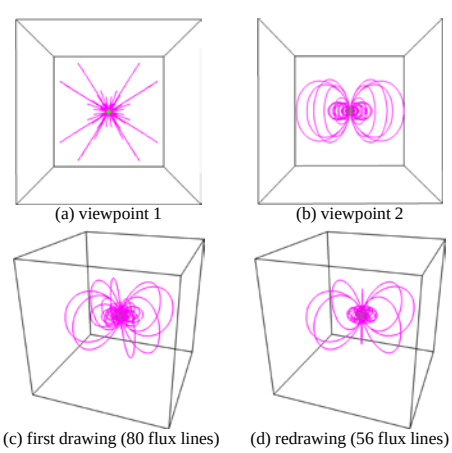


Fig. 6. Visualization of 80 magnetic flux lines for model of single permanent magnet model. (a)-(c) 80 lines visualized from different viewpoints – initial drawing. (d) 56 lines visualized when changing the number of lines for the second drawing.

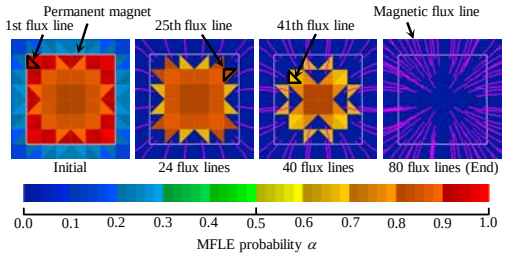


Fig. 7. Change of MLFE probability α distribution on the cross section of permanent magnet until the allocation of all magnetic flux lines is determined by the proposed method, when the 1st, 25th, 41th, and whole 80 magnetic flux lines (from left to right) are computed. After visualizing the whole 80 magnetic flux lines, the MLFE probability α is 0 everywhere (blue elements everywhere).

TABLE I
THE NUMBER OF MAGNETIC FLUX LINES AND ELEMENTS

Method	Old Method [6]	Proposed Method
# of elements	79507	384000
# of magnetic flux lines	50	80

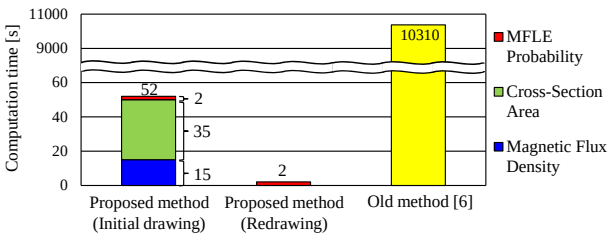


Fig. 8. Comparison of computation time in the old and the proposed method. In the proposed method, breakdown of computation time is shown.

computation time of the old method is shown, and almost the same computation time is wasted for the second drawing.

3) Decreasing the Computation Time during Redrawing

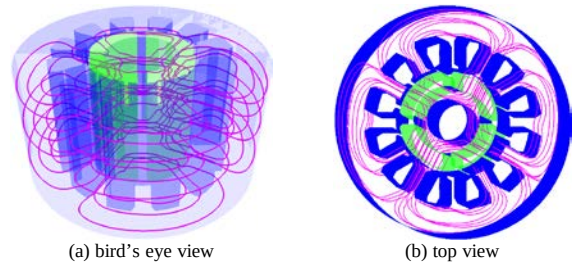
Fig. 8 also shows the breakdown of the total computation time of the proposed method and for each process separately. Since during redrawing process some lengthily processes are omitted, i.e., the computation of the magnetic field $\boldsymbol{B}_i$ and cross-sectional area S_i are omitted since this calculation have already been done during the initial visualization process, during redrawing decreasing of the total computational time is significant. Consequently, these facts allow users interactive adjustment of the number of magnetic flux lines to be visualized. As shown in Fig. 8, the computation time of the proposed method decreased from 52 s for the first drawing, down to only 2 s for the next drawing.

B. Motor Model

Next, we applied it for visualization of magnetic flux lines for more complex model of a SPM motor [10]. Fig. 9 shows the visualization result of this model. In general, it is more difficult to visualize the magnetic flux lines due to multiple electromagnetic sources. However, as shown in Fig. 9, the proposed method provides accurate allocation of the magnetic flux lines even for such electromagnetically complex models.

IV. CONCLUSION

In order to decrease the computational cost and increase the



(a) bird's eye view (b) top view

Fig. 9. Visualization of magnetic flux lines allocated by the proposed method for a model of SPM motor in 3-D space.

versatility of the old visualization methods [5], [6], in this paper, the authors proposed a new visualization method. The proposed method computes the so-called "*magnetic flux line existence* (*MFLE*) *probability*", as a major parameter for adequate allocation of the magnetic flux lines to be visualized. The major advantage of the proposed method is its short computation time, especially for redrawing various numbers of flux lines in the analysis region, which enables this method to be used for any interactive visualization systems.

In order to verify the effectiveness of the proposed method, two models with their results were presented. From these results, one can easily confirm that the allocation of the magnetic flux lines obtained by the proposed method satisfies the rule (i), the computation time is much shorter than with the old method, and the application for magnetic flux visualization of a complex electromagnetic device is easily attainable.

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