A New Interactive Visualization System with Force Feedback for Education in Electromagnetics

Yutaka Matsubayashi, So Noguchi, Hideo Yamashita

Abstract – This paper describes the interactive visualization system with force feedback device for educational purpose in electromagnetics. For the common electromagnetic field visualization systems, the magnetic force is represented by the size and direction of arrow or cone. However, in reality, we surely recognize forces through a part of our body, such as hands. It is the reason why we have developed the system that makes a user feel the magnetic force in electromagnetic field by using the haptic interface. The proposed visualization system provides possibilities a user recognize the commonly invisible phenomenon in electromagnetic field through ones eyes and hands, thus it can be very useful as an educational tool.

***Index Terms*— Visualization, Interpolation Method, Force Feedback, Haptic Interface**

I. Introduction

In electromagnetic field problems, the visualization of numerical analysis results helps us to understand the phenomena. We have already proposed several visualization tools for electromagnetic field computation for the purpose of grasping the physical behavior of the analyzed field problems [1–3]. However, the electromagnetic field analysis usually takes a significant computation time. Recently, for an educational tool in electromagnetics, we have developed the interactive system for visualizing computed results [4]. This visualizing system could instantly visualize the field distribution even if a movable object is moved to an arbitrary position. The main features of this visualization system were:

- Using several data sets obtained numerically for few user-defined model configurations, this system could compute and interactively visualize results for any other model configuration which was bounded by those previously computed configurations utilizing simple interpolation technique.
- It could also interactively display the magnetic vector potential distribution, the magnetic flux density distribution, the magnetic flux lines and the magnetic flux density vector or any combination of them, simultaneously.

In this paper, we propose enhancement of this interactive system that can not only visualize the field distribution, however, adding a new important property of making a user feel the magnetic force in 2D electromagnetics during the visualization. In a common electromagnetic field visualization systems, the magnetic force is represented by the size, color and the direction of an arrow or a cone. However, in reality, we frequently recognize forces through a part of our body, such as hands. That is the main reason why we have developed a new system that makes a user feel the magnetic force in electromagnetic field by using the haptic interface. Since this system makes a user recognize the invisible phenomenon in electromagnetic field through our eyes and hands, we are of the opinion that such visualization system could be very useful as an educational tool.

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Y.Matsubayashi, S.Noguchi and H.Yamashita are with the Department of Electrical Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, JAPAN (yama@eml.hiroshima-u.ac.jp; noguchi@eml.hiroshima-u.ac.jp).

II. Interactive Visualization System with Force Feedback

The proposed system is composed of the two parts, a module for visualizing the distributions and a module for force feedback to a user using the haptic interface. The haptic interface is the PHANToM, while the library to control the PHANToM is the GHOST SDK [5].

A common electromagnetic field visualization system usually displays computed distributions, such as the magnetic flux density and/or the magnetic flux lines, using simple display techniques. The force information, such as the magnetic force, is usually displayed using an arrow or cone gismos. On the other hand, our proposed system can not only visualize the field distribution, but also, at the same time, make a user feel the magnetic force with his body. Therefore, the proposed system helps to understand the electromagnetic field deeper than a common visualization system that uses only the graphical visualization.

As shown in Fig. 1, the proposed system calculates the field distributions, and consists of a user display, a personal computer for calculating the distributions and the magnetic force, the haptic interface that feed back to a user the magnetic force and the mouse that operates event processing.

Next, the processing procedure of the proposed system is explained. Initially, a user inputs the position of the movable object by the stylus pen of PHANToM. Second, after we visualize the field distribution in the case of the user-defined position of the movable object, using the proposed system we calculate the magnetic force by means of a bi-linear interpolation on-line. In the same time, the user can feel the magnetic force through the stylus pen of the PHANToM. Therefore, this system can visualize the field distribution and make a user feel the magnetic force in real time. Changing the position of the object, and respectively the distribution, one can change using a pop-up menu and the mouse.

An example, where the proposed system is used, is shown in Fig. 2. The applied model is shown in Fig. 3. This same model was applied in the previous paper, where we point out that the visualization error was acceptably small from the engineering point of view [4]. By means of this new visualization system, now, the user can observe not only the distributions, such as magnetic flux density and magnetic flux line, but also he can feel the magnetic force, simultaneously.

The basis for the proposed system was already proposed interactive visualization system for the display portion of the distributions [4]. Therefore, in what follows, we only describe the techniques used for the visualization of the distributions and for the calculation of the electromagnetic forces.

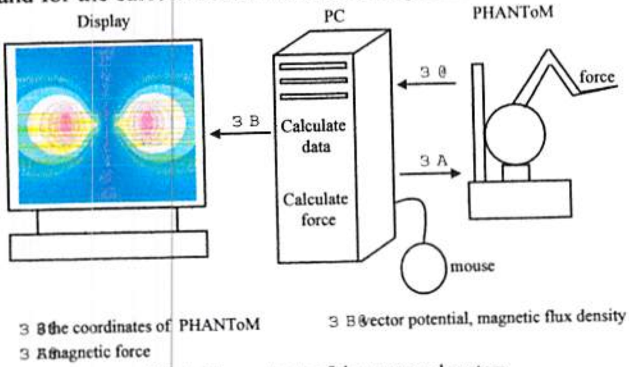


Fig.1: The contents of the proposed system.

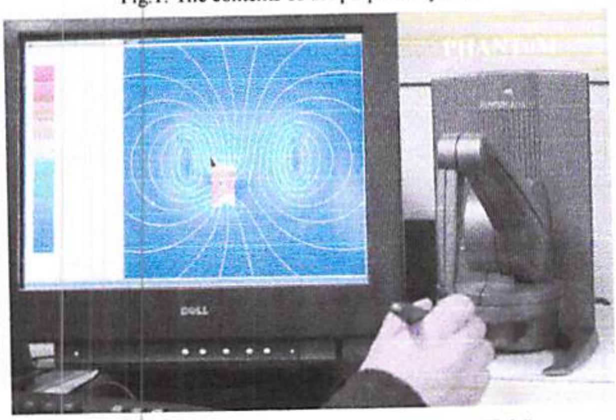


Fig.2: Field distribution map and haptic interface (PHANToM).

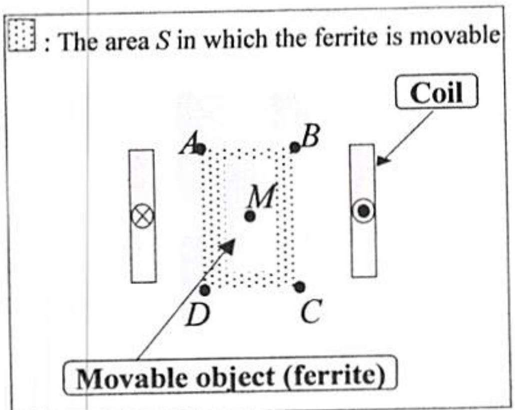


Fig.3: Simple 2D model

A. Interpolation Method

1) Interpolation Method for the Field Distribution

Initially, for simple 2D model the exact field distributions are computed at four discrete positions of the movable object inside the analysis domain, positions *A*, *B*, *C*, and *D* as shown in Fig. 3.

The interpolation procedure used to obtain unknown distributions for an arbitrary position of the movable object is briefly summarized below:

Preprocessing Step:

Step1: Define the corresponding areas and the area outside the interpolation domain for each of the pre-computed configurations. These areas we call *corresponding blocks* (see Fig. 4).

Step2: Decompose each area (0.9) into an $i.j$ 2D grid and compute V_{paij} at each grid point, where i is the number of division along x-axis defined by each *corresponding block*. Similarly, j is the number of divisions along y-axis, V is a physical value (magnetic vector potential value or magnetic flux density value) , p is the position index of the pre-computed configuration ($A.D$), a is the index of each *corresponding block* and the area outside the *corresponding blocks* (0.9).

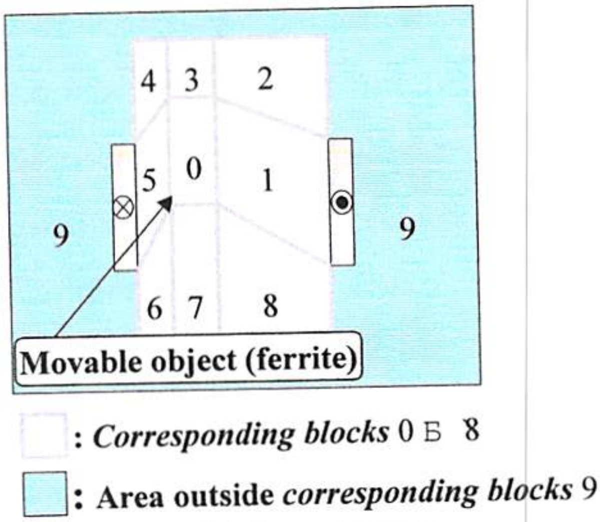


Fig.4: Corresponding Blocks

Processing Step:

Step1: Arbitrary moves the movable object inside the display area M inside S using *move & drag* operations described above;

Step2: Decompose the display area into a set of visualization blocks and find matching pairs of blocks, among these new generated visualization blocks and the corresponding blocks constructed in the preprocessing step;

Step3: Decompose each area (0.9) constructed at *Step2* into the same number of 2D grid points as preprocessing ones.

Step4: If four or more analysis results are prepared on different positions, chose three best applicable. If four results are prepared on different positions, chose all four. As an example, as shown in Fig. 5, when the movable object position M is included in the triangle AED, the analysis result of A, E, and D are chosen.

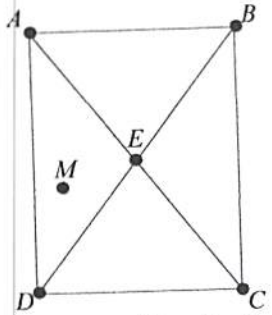


Fig.5: Decomposition of the triangle

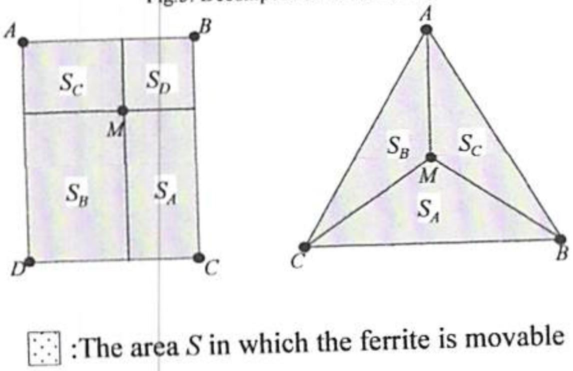


Fig. 6: The area coordinates for each shape

Step5: If four results are chosen, calculate the area coordinates S_A . S_D at point M inside the area S (see Fig. 6). If three results are chosen, calculate the area coordinates S_A . S_C at point M inside the area S (see Fig. 6).

Step6: Calculate the area coordinates S_A . S_D at point M inside the area S (see Fig. 6);

Step7: Calculate physical value V_{aij} at each grid point of a *corresponding block* utilizing the bi-linear interpolation method given below using physical value V_{paij} and the area coordinates S_A . S_D;

$$V_{aij} = V_{Aaij} \cdot S_A + V_{Baij} \cdot S_B + V_{Caij} \cdot S_C + V_{Daij} \cdot S_D \quad (1)$$

Step 8: Finally, execute the above procedures for each and every grid point in order to obtain the total distribution.

This procedure is enough fast to enable interactive visualization, therefore, user can obtained the desired magnetic vector potential or magnetic flux density at any positions M in S in real time using move operation of the stylus pen of a haptic interface.

2) *Interpolation Method for the Magnetic Force*

In the previous section we described the interpolation method in order to obtain the unknown distributions, while in this section we describe the interpolation method for calculating the magnetic force. The idea behind this method is very similar to the previous one. We use simple 2D model (see Fig. 3) and describe the interpolation procedure in order to obtain an unknown magnetic force. In order to obtain better accurate distribution by interpolation, we exhort to use four pre-computed results (see Fig. 4) for the position A.D. The interpolation procedure to obtain the unknown magnetic force for an arbitrary position of a moving object is briefly summarized below:

Preprocessing Step:

Step1: By means of the finite element method, the field distributions are computed in the case of few predifined positions of the moving object, e.g. positions A, B, C and D as shown in Fig.2.

Step2: The magnetic force of the moving object at each node of the finite element mesh is computed utilizing nodal force method [6]. The resultant magnetic force $F_P=(F_{Px},F_{Py})$ of the moving object is obtained by summing up the magnetic forces at each node. Subscript P indicates the position of the moving object, and subscript x and y are the x and y components of the magnetic force of the same moving object, respectively.

Processing Step:

Step1: Arbitrary move the moving object inside the display area M inside domain S using the PHANToM's stylus pen.

Step2: Calculate the resultant magnetic force $F_M=(F_{Mx}, F_{My})$ utilizing the bi-linear interpolation of the area coordinates, which are calculated in previous section (Fig. 5), and obtain the magnetic force.

$$\begin{pmatrix} F_{Mx} \\ F_{My} \end{pmatrix} = \begin{pmatrix} F_{Ax} \\ F_{Ay} \end{pmatrix} \cdot S_A + \begin{pmatrix} F_{Bx} \\ F_{By} \end{pmatrix} \cdot S_B + \begin{pmatrix} F_{Cx} \\ F_{Cy} \end{pmatrix} \cdot S_C + \begin{pmatrix} F_{Dx} \\ F_{Dy} \end{pmatrix} \cdot S_D \quad (2)$$

$$\begin{pmatrix} F_{Mx} \\ F_{My} \end{pmatrix} = \begin{pmatrix} F_{Ax} \\ F_{Ay} \end{pmatrix} \cdot S_A + \begin{pmatrix} F_{Bx} \\ F_{By} \end{pmatrix} \cdot S_B + \begin{pmatrix} F_{Cx} \\ F_{Cy} \end{pmatrix} \cdot S_C \quad (3)$$

Using the above procedures, one can obtain the magnetic force of the moving object for any arbitrary position. The magnetic force obtained by the interpolation is fed back to an observer's hand through the PHANToM's stylus pen. The user can observe the distributions obtained at section 2.1, and simultaneously, he can feel the magnetic force with his hands. The preprocessing steps, which are described in sections 2.1 and 2.2, have to be executed only once at the time of the system's starting. On the other hand, processing step is executed whenever the user makes the moving object move at the user-desired position.

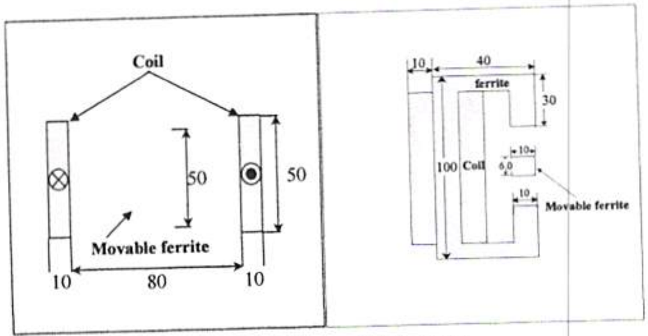
In the proposed system, moving the object at the desired position in the display screen is facilitate easily by means of the PHANToM's stylus pen. Furthermore, the user can chose the user-defined distributions from a pop up menu by using a mouse. Using these two operations, the user can simultaneously feel the magnetic force and also observe the distributions, such as the magnetic flux density, the magnetic flux lines and the magnetic vector potential.

III. Application Models

Proposed visualization system was applied to two models shown in Fig. 7. In the Model *#1*, a movable ferrite was used, and in the Model *#2*, a movable ferrite under the C-type electromagnet was considered. Obtained results for two arbitrary positions of the ferrite (Model #1 and Model #2) are given in Fig. 7, respectively. For both models, interpolation was performed using four model configurations with pre-computed values of the magnetic vector potential and magnetic flux density. The calculation time was less than a second for each arbitrary position. Such short computation time enables real time interaction between the user and the system.

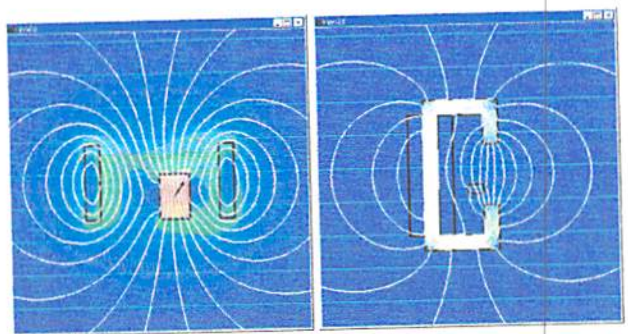
For the application result of Fig. 8, magnetic flux line and the distribution of magnetic flux density, and magnetic force are displayed. The magnetic force is represented by the size and the direction of an arrow. These models were also applied in the previous paper, and the error was acceptably small from the engineering point of view [4]. In that case, that the error is large, preparing more analysis results improves the accuracy of our system. Adding additional results obtained by the finite element method analysis provides the error for interpolation to become acceptably smaller.

The field distributions and the magnetic force are calculated by the bi-linear interpolation of their values obtained in the preprocessing step in less than 1s CPU. Therefore, the user can observe the distributions and feel the magnetic force through the stylus pen of PHANToM, respectively, almost on-line.



(a) Model #1 (b) Model #2

Fig. 7: Application models



(a) Model #1 (b) Model #2

Fig. 8: Application results

IV. Summary

We propose a new interactive visualization system with force feedback for education in electromagnetics. By using the visualization system with force feedback (haptic interface), one can visualize and feel the magnetic force simultaneously. Utilizing a simple interpolation method, the proposed system enables interactive visualization. Therefore, the proposed system has a main feature that the user can visualize the distributions and feel the magnetic force simultaneously, which provides understandings of the physical phenomenon deeper than by using only the graphical visualization. Accordingly, the proposed system is very useful for an educational tool.

The future works are concentrating in extension of the proposed system into three dimensions. In parallel we have to consider the time-delay caused by the increase of calculation time and the examination of the display technique. Additionally, we need further testing of the proposed technique by various users to identify the advantages and weaknesses of the proposed system and to analyze user's opinions to improve the quality of our visualization system.

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