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Daejeon, South Korea, June 18–22, 2017
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Chairman’s Foreword

The 21st edition of the International Conference on the Computation of Electromagnetic Fields (Compumag 2017) took place from June 18 to 22, 2017, at the Daejeon Convention Center (DCC), in Daejeon—referred to as “Asia’s Silicon Valley”—in South Korea. The conference has been held every two years since the first meeting in Oxford, U.K., in 1976, and has provided a discussion forum for the international community of researchers studying electromagnetic fields. Compumag provides a great opportunity to exchange ideas productively, contributing to the development of innovative technologies and new research areas. We hope computational electromagnetics will continue to prosper, and electromagnetic systems will improve partly thanks to Compumag 2017.

As a premier technical conference on the numerical computation of electromagnetic fields, Compumag 2017 attracted over 400 researchers from 29 countries in five continents. The fact that 33% of the attendees were students demonstrates the attractiveness of the relevant research fields, including mathematical modeling and formulations, multi-physics and coupled problems, novel computational methods, numerical techniques, optimization and design, etc. The Technical Program Committee of the Conference received 730 papers covering 12 major topics. The digests were thoroughly reviewed, each by at least two reviewers, following Compumag regulations and IEEE TRANSACTIONS ON MAGNETICS standards. In total, 454 papers were selected for presentation, of which 122 were from China, making the largest contribution, followed by South Korea with 90 and Japan with 45. Thanks to the enthusiasm and effort of a number of researchers, leading-edge research on novel techniques and methodologies was presented, especially in optimization and design with 134 papers, static and quasi-static fields with 51, and numerical techniques with 45. In addition, a variety of other topics were covered in oral sessions, with a total of 147 participants sharing their research findings through active debate and discussion. We hope this sharing of ideas at Compumag 2017 will contribute to the technological development of computational electromagnetics.

Compumag 2017 featured 29 poster and 8 oral sessions, attended by 417 delegates from 29 countries. As the conference was hosted by the DCC with large exhibition halls, we were able to create a wonderful atmosphere for enthusiastic discussions. In particular, during the conference, the Rita Trowbridge Award was presented to those young researchers who demonstrated the highest technical quality throughout the conference. The awards committee was chaired by Professor Ruth Sabariego, KU Leuven, Belgium. The first prize was awarded to Sebastian Schuhmacher, Magstadt, Germany, and runner-up commendations to Ji Qiao, Tsinghua University, China; Shingo Hiruma, Hokkaido University, Japan; and Bernard Kapidani, University of Udine, Italy.

All authors of the papers presented at the conference were invited to submit extended and enhanced manuscripts for publication in IEEE TRANSACTIONS ON MAGNETICS. We hope that you will find all work published useful and inspirational for the next Compumag.

Compumag 2017 was organized thanks to the effort of many professors and students from several universities in South Korea. My deep gratitude goes to all volunteers, reviewers, and all those who contributed to the organization. I would particularly wish to thank Prof. Chang-Seop Koh, Prof. Kyung Choi, Prof. Sang-Yong Jung, and Prof. Jang-Young Choi, for their hard work and for making the event such a success. Finally, on behalf of the organizers, I want to thank all the participants and I hope you have wonderful memories of Compumag 2017. We now all look forward to Compumag 2019 in Paris.

HYUN-KYO JUNG, General Chair
Compumag 2017
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An Adaptive FEM Based on Magnetic Field Conservation Applying to Ferromagnetic Problems

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We have previously been proposed a novel adaptive finite-element method (FEM) based on a magnetic field conservation indicator and a non-conforming mesh-refinement technique. However, we have applied to a very simple model consisting of a single permanent magnet for basic verification of the proposed method. In this paper, we have improved an error indicator, and tried to apply a newly proposed adaptive FEM to more complicated models, where ferromagnetic material is included. The newly proposed method is superior in torque error estimation to the Zienkiewicz–Zhu (ZZ) error estimation method in a 3-D permanent magnet motor model.

Index Terms—Adaptive finite-element method (FEM), error estimation, magnetic field conservation, non-conforming mesh.

I. INTRODUCTION

A NOVEL adaptive finite-element method (FEM) has previously been proposed utilizing a magnetic field conservation evaluation as an error indicator and a non-conforming mesh-refinement technique as a mesh-refinement scheme [1]. Our goal is to improve the simulation accuracy with less number of elements. Though the performances of PCs are enhanced, the generation of an unnecessary large number of elements is undesirable to adaptive FEMs.

Some error indicators were proposed [2]–[5], and an error indicator based on the conservation of magnetic field \(H\) on the interface between two elements [1], [5] are very promising from the mathematical viewpoint. Meanwhile, a few kinds of non-conforming techniques were also proposed such as the discontinuous Galerkin method [6], the mortar FEM [7], and the mesh interpolating method [8]. The interpolating method is well suited for the proposed adaptive FEM [1].

The previously proposed adaptive FEM resulted in the generation of a suitably dense mesh with less number of elements. The proposed method has two advantages: 1) it is possible to indicate an error on element surfaces between different materials and 2) it is easy to subdivide badly evaluated elements into smaller ones, even though they are elements on object boundary. That is, it is easily applicable to a complicated simulation model including iron cores or plural kinds of materials. However, we have never shown any result of models containing multiple materials.

In this paper, first of all, two modifications on the error indicator are shown. Then, the proposed adaptive FEM is applied to two models: a single permanent magnet and iron core model, and a surface permanent magnet (SPM) motor model. In the SPM motor model, the computation of torque is enhanced using the proposed error indication. It is well known that it is difficult to compute the torque without

\[
d_{i,j} = \int_S (\mathbf{H}_i \times \mathbf{w}_j) \cdot \mathbf{n}_i dS \quad (i = 1, 2 \text{ and } j = a, b, c)
\]

(1)

where \(i, j, S, \mathbf{H}, \mathbf{w},\) and \(\mathbf{n}\) are the indices of adjacent elements and edges (see Fig. 2), the element surface, the magnetic field strength, the vector interpolation function, and the unit vector normal to the element surface \(S\), respectively. However, on the surface of permanent magnet, the indicator (1) must be

\[
d_{i,j} = \int_S (\mathbf{H}_i - K_i) \times \mathbf{w}_j \cdot \mathbf{n}_i dS
\]

(2)
where $K$ is the equivalent surface current on the surface of permanent magnet.

Due to the magnetic field conservation, the following equations with respect to all three edges per element surface must hold:

$$D_j = d_{1,j} + d_{2,j} = 0 \ (j = a, b, c).$$

(3)

As a result of the conventional edge-based FEM, the values of $D_j$ are not zero. Therefore, as the final error indicator $E$ of the previous paper [1], we proposed

$$E = \max(|D_a|, |D_b|, |D_c|).$$

(4)

However, the value of the larger error indicator $E$ strongly depends on the angle between the vector $(H - K)$ and the edges. Therefore, we have newly proposed the following error indicator:

$$\tilde{E} = (|D_a|^2 + |D_b|^2 + |D_c|^2)^{\frac{1}{2}}.$$  \hspace{1cm} (5)

Using (5), the new error indicator $\tilde{E}$ is independent of the angle between the vector $(H - K)$ and the edges. Since the component of magnetic field $H$ tangential to the element surface is continuous on the boundary of different materials, this error indicator becomes useful, robust, and effective.

**B. Non-Conforming Mesh Refinement Scheme**

A mesh-refinement task is burdensome in the conventional adaptive FEM. As a mesh-making method, the Delaunay triangulation method is well known and widely used. However, many ill-quality elements, such as flat or inside-out elements, are often generated with adaptive steps. In the proposed mesh-refinement scheme, one element indicated with a large error is subdivided into eight smaller elements. Actually, using the above error indicator, two elements are simultaneously evaluated, so two elements with a large error become 16 smaller elements. Some of these elements to be subdivided have a surface sharing with an element not to be subdivided, a non-conforming surface is generated there (see Fig. 3). Since nodes are placed on edges for element subdivision, the non-conforming refinement scheme is easily applicable to elements even on the boundary of analysis objects. The level difference of subdivision between two neighboring tetrahedrons is limited to two, in order to avoid the sudden change of mesh density. The large mesh-size difference would make it difficult to solve the system equations.

As shown in [1], the proposed method reuses all the created constitutional matrices $C$ on every adaptive step. As the result, on the $i$th step, we can obtain the following system:

$$C_i \cdots C_i^L C_i \cdots C_i \tilde{a}_i = C_i \cdots C_i^L b_i$$

(6)

where $L$, $\tilde{a}$, and $b$ are the stiffness matrix, the vector potential on master edges, and the source vector, respectively.

In our non-conforming scheme, the larger surface is employed as a slave, and the smaller as a master. On the geometrical relation shown in Fig. 4, the relation between the master and slave is obtained as follows:

$$C\tilde{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \\ a_9 \end{bmatrix}.$$  \hspace{1cm} (7)

Using the constitutional matrix (7), the vector potentials on subdivided edges are unknown, meanwhile those on the parent edges before subdivision are obtained from the interpolation of subdivided edges.

On each adaptive step, the system of equations is not renumbered and not compressed in our program code. The matrix diagonals on the slave edges are 1, meanwhile the other elements are 0. Although the memory wastes, it is easy to make a program of adaptive FEM as a hierarchical repeatable function. The obtained system is solved by the incomplete Cholesky conjugate gradient.

**III. APPLICATIONS**

To confirm the validity of the proposed adaptive FEM, it was applied to two models including ferromagnetic materials: a simple model and an SPM motor model.

**A. Simple Model (Permanent Magnet and Iron Core)**

The proposed adaptive method is robust to models consisting of multiple materials with different permeability, such as a permanent magnet and an iron. To show the effectiveness of the proposed adaptive FEM, it is applied to a model consisting
The specifications of a permanent magnet and an iron, as shown in Fig. 5. Fig. 5 also shows the simulation specifications.

The initial rough mesh of 18,838 elements was created by commercial software. The magnetic energy error of the initial mesh was 7.48% as a true value of simulation result with a large number of elements. Fig. 6 presents the magnetic energy error as a function of number of elements. In the first few steps, the magnetic field error is drastically reduced. At the fifth adaptive step, the error decreased to 0.06% with 708,989 elements.

Fig. 7 shows the flux line maps visualized from the simulation result at the fifth adaptive step. The proposed adaptive FEM works as a smoother of flux lines by improving the discontinuity of the tangential component of magnetic field. Every flux line in Fig. 6 looks like enough smooth.
of the proposed method is drastically enhanced due to the improvement of the discontinuity of the tangential magnetic field component. The elements around the air gap are well subdivided as shown in Fig. 12. The final values are 0.7 mNm in the proposed method and 48.4 mNm in the ZZ method. Meanwhile, the magnetic energy error of the proposed method does not converge to zero. The ZZ method is superior in the magnetic field energy evaluation because it evaluates magnetic field energy continuity between adjacent elements as an error indicator.

Next, Fig. 13 indicates the element subdivision map in the proposed adaptive FEM. On every step from the initial to the third subdivision mesh, the elements around permanent magnet and air gap are badly evaluated. Fig. 14 shows the element subdivision map with the adaptive step in the ZZ method. As the adaptive step proceeds, the elements in the entire region are ill evaluated. Since the small elements are distributed in the entire region, the accuracy of the magnetic field energy is enhanced but the torque accuracy is not improved.

IV. CONCLUSION

The proposed method was applied to two models containing ferromagnetic materials to show the validity. Since the continuity of the magnetic field tangential to element surface was evaluated in the proposed adaptive FEM, the accuracy of torque computation in the motor model was enhanced. However, the magnetic field energy was badly evaluated.

In near future, the proposed method must be modified to enhance the magnetic field energy error. One reason of the large energy error is that the magnetic field \( H \) is too high in the air gap, and the elements in the air gap are over evaluated in the proposed adaptive FEM.

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