Extraction and Visualization of Semitransparent Isosurfaces for 3-D Finite Element Analysis

Hironori Matsuda, Vlatko Cingoski, Kazufumi Kaneda and Hideo Yamashita
Faculty of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashihiroshima 739-8527, Japan

Jun Takehara and Ikuo Tatewaki
Chugoku Electric Power Co., Inc., Technical Research Center, 3-9-1, Kagamiyama, Higashihiroshima, 739-0046, Japan

Reprinted from
IEEE TRANSACTIONS ON MAGNETICS
Vol. 35, No. 3, May 1999

Extraction and Visualization of Semitransparent Isosurfaces for 3-D Finite Element Analysis

Hironori Matsuda, Vlatko Čingoski, Kazufumi Kaneda and Hideo Yamashita
Faculty of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashihiroshima 739-8527, Japan

Jun Takehara and Ikuo Tatewaki
Chugoku Electric Power Co.,Inc., Technical Research Center, 3-9-1, Kagamiyama, Higashihiroshima, 739-0046, Japan

Abstract—**One of the most challenging idea is to use an isosurface visualization for the post-processing of the large amount of output data obtained from various numerical method, such as the finite element method (FEM). In this paper, we present a newly developed multipurpose visual system for 3-D display of scalar variables using isosurfaces visualization. The proposed visualization method is based on extraction of a set of triangular patches using improved marching cube algorithm, construction of the isosurface and their interactive 3-D display.**

Index terms—**Finite element methods, magnetic fields, marching cube method, scientific visualization, electromagnetic compatibility.**

I. Introduction

Recent development in computational technology have challenged analysts to perform numerical analysis of increasingly complex and higher dimensional problems even on personal or low-end workstations. At the same time, post-processing techniques also have undergone tremendous development, especially in the domain of scientific visualization, simulation and animation [1]. The authors have recently proposed several methods for post-processing of the 3-D FEM results, among them: (1) visualization of flux density on cross sections and/or object surfaces using a mapping function from physical values to quasi-color scale [1], (2) analytical method for magnetic flux lines visualization [2], and (3) visualization of the flux density distribution using volume rendering technique [3].

For users, the most important question is to choose a method that most adequately expresses their visualization needs. For example, using cross section and/or object surface visualization, one can easily grasps the physical values on that particular cross section or object surface only, while using volume rendering techniques, the user can observe the physics quantity distribution inside the entire analysis space. Although the magnetic field distribution has vector field properties, sometimes, it is very important to visualize only its intensity distribution as a scalar. For example, recently became very important to know the exact magnetic field intensity distribution which surrounds some electromagnetic device or equipment as in case of electromagnetic compatibility or biomedical analysis. In such cases a display method for scalar quantities using isosurface visualization method becomes indispensable.

In this paper, we propose a method for easy extraction and visualization of semitransparent isosurfaces in 3-D domain. The method is fast enough to provide interaction between the user and the displayed results almost in real time. The visibility of the generated image is further enhanced using new method for rendering of the extracted isosurfaces utilizing point light sources. The main features of the proposed visualization method can be summarized as follows: (1) For isosurface extraction it uses directly the finite element mesh previously developed for computational purposes, (2) it utilizes the modified marching cube (MC) algorithm which can accommodate various types of finite elements beside the cube element as in its original version, (3) it is fast enough to enable interactive visualization of several isosurfaces simultaneously without clutter, and (4) it is robust and general and can be used for visualization of any kind of scalar physical values.

II. Proposed Visualization Method

A. Extraction and Construction of Isosurfaces

Similarly to the 2-D approach where the isolines represent lines that connect all points with equal scalar values, the concept of isosurface is just a simple 3-D extension of this idea; thus isosurfaces represent surfaces with equal scalar value of a physical variable. Generally it is too complicated to represent easily an arbitrary 3-D isosurface using simple mathematical expression. Therefore, usually an isosurface is constructed by gathering simple 2-D patches with the same physical value, e.g. triangular patches. For generation of such simple 2-D patches we applied the marching cube (MC) algorithm, that is the method for composing desired surface by meeting together a large set triangle patches with same physical values extracted from the cubes of same size [4], [5]. The MC algorithm was initially proposed for composition of 3-D objects from several cross sectional images obtained from computer tomography scans. For our purposes, we improved the original MC algorithm to enable construction of isosurfaces using computational FE mesh division (various shapes of finite elements such as tetrahedrons, prisms or hexahedrons) instead of only cubes with the same size.

Manuscript received June 3, 1998.
Hideo Yamashita, +81 824-24-7665, fax +81 824-22-7195, yama@eml.hiroshima-u.ac.jp, http://www.eml.hiroshima-u.ac.jp/

0018-9464/99$10.00

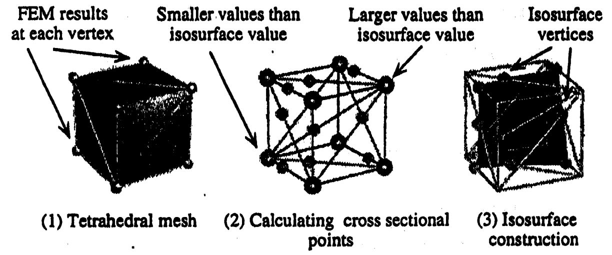

Fig. 1. Extraction of arbitrary isosurface.

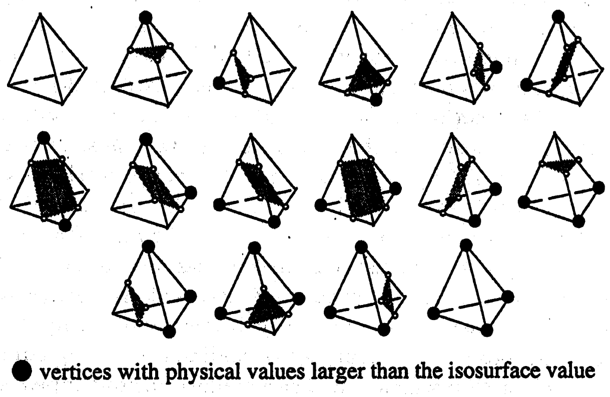

Fig. 2. Triangular patterns for tetrahedral finite element.

A simplified algorithm for extraction of 2-D patches in case of a tetrahedral FE mesh is given in Fig. 1. First, the values of a physical variable are computed by means of the FEM at each vertex. Second, each vertex value is compared with user defined isosurface value making separation between vertices with larger and vertices with smaller value than the user defined one. Next, by means of linear interpolation, we computed the point of cross section between the isosurface and each edge that has one vertex with larger and one vertex with smaller value than that of the isosurface. Finally, we connect the generated cross sectional points into triangular patches and the generated set of triangular patches into the desired 3-D isosurface as shown in Fig. 1.

Although the above described procedure seems computationally expensive, the extraction of triangular patches becomes a straightforward procedure if we take into account that, for example, in case of tetrahedron the entire subset of possible triangular patches can be classified into only 16 (2^4) patterns as shown schematically in Fig. 2. Therefore, it is possible to construct and memorize the precomputed lookup tables for each of the utilized FE shapes making the isosurface extraction procedure fast and easy. To increase the applicability of our method, we developed separate lookup tables for tetrahedron, prism and hexahedron as most widely used type of finite elements for electromagnetic field analysis. This general algorithm for construction of the triangular patches by using lookup tables is shown in Fig. 3.

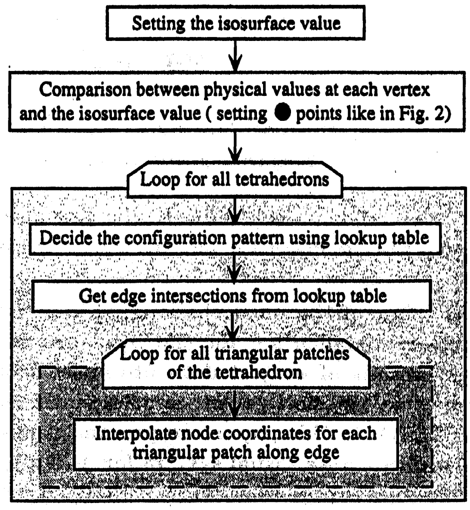

Fig. 3. Algorithm for construction of triangular patches.

B. Visualization of Isosurfaces

Visualization of an isosurface as a 3-D object on a 2-D screen or as a 2-D image is very complicated task. To achieve depths and 3-D appearance of the generated image some computer graphics techniques should be employed. First of all, in our method, isosurfaces are displayed semi-transparently which enables easy observation of isosurfaces and grasping the mutual relationship among the pile of several isosurfaces. The display color of a triangular patch is interpolated utilizing color values I_p computed at each of its vertices according to the following equation:

$$I_p = I_d \left(\frac{1}{cos\theta}\right) \quad , \tag{1}$$

where I_d is the basic color of that isosurface. The intensity color values I_p and I_d consist of red (R), green (G), and blue (B) color components respectively, while θ is the angle between the ray vector and the outward normal of the isosurface patch as shown in Fig. 4b. However, since the normal vector of each patch is different as shown in Fig. 4a, one vertex could have different color values computed using different adjoint triangular patches. Therefore, we first compute the normal vector at each vertex as an average value of normal vectors of all triangular patches that has that vertex in their list of vertices, followed by the color computation at each vertex according to (1). Regarding illumination, an isosurface is not simply diffuse illuminated but rather it reflects light towards the observer or shines by itself. Therefore, as the angle between the outward normal and a ray vector approaches 90°, the color intensity of the surface increases. As a result, the brightness of the isosurface's boundary observed from the viewpoint increases, and consequently the outline of the surface and the entire form of the isosurface becomes more visible. A comparison between ordinary diffuse illumination method and the illumination method employed in our visualization is shown in Fig. 5. As can be seen, our method provides clearer image and emphases

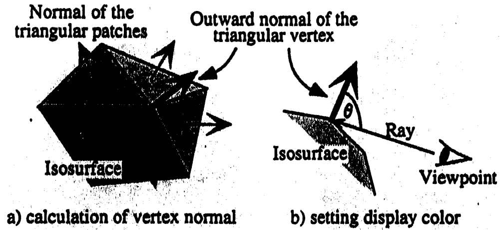

Fig. 4. Definition of the illumination angle θ.

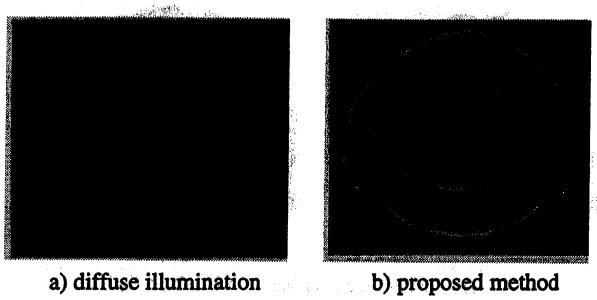

Fig. 5. Comparison between illumination methods: (a) Diffuse illumination (b) Proposed method.

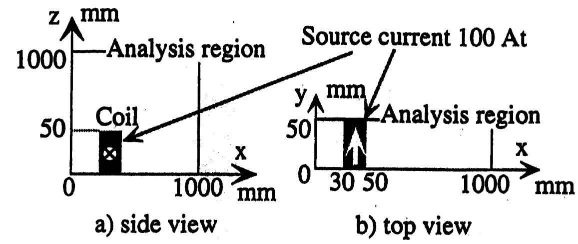

Fig. 6. A 3-D verification model.

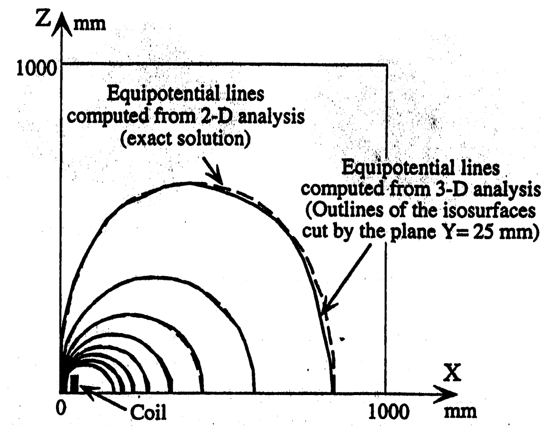

Fig. 7. Verification of the precision.

the shape and outline of each isosurface better than the original diffuse illumination. This illumination method is especially efficient for display of several isosurfaces simultaneously with high visual clarity.

In order to improve the visual impact of the proposed method, we additionally developed two computation procedures: (1) to visualize a cut-view of the isosurfaces by the arbitrary cross section plane, and (2) to visualize the object surfaces inside the analysis domain. The first procedure provides easier understanding of the structure and relations between several isosurfaces in the 3-D space, while the second one provides better understanding of the analysis domain and physical meaning of the visualized quantity. For user, drawing objects such as coils, ferrites, eddy-currents conductive plates, etc., together with the generated isosurfaces makes it geometrically easier to understand the results and their correlation with the entire analysis domain. In our method, drawing of the objects is enabled by extraction and display of the surface triangular patches of only the outermost finite elements that describe the particular object.

C. Verification of the Proposed Visualization Method

To verify the usefulness of the our isosurface extraction and visualization technique, first we must test its accuracy and precision. We must verify the precision that can be achieved when an arbitrary 3-D isosurface is approximated by set of 2-D triangular patches. For that purpose, we developed 2-D and 3-D model of a bus-bar problem shown in Fig. 6. Next, we computed the equipotential lines in 2-D domain using the results obtained by the 2-D FEM for the extremely dense FE mesh in order to use these results as the exact solution. Then, we performed 3-D FEA and computed a set of isosurfaces with the same values as those of the 2-D equipotential lines. Fig. 7 shows the comparison between 2-D equipotential line distribution (dotted lines) which were considered as the exact values, and the results obtained using a cut-view of the generated isosurface distribution on plane $Y = 25\ mm$ (solid lines). As can be seen, the agreement between both results is almost excellent for the entire analysis domain.

III. Applications

The proposed visualization method was applied for isosurface visualization using two models: a simple test model which consists of a one loop coil wound around square shape ferrite shown in Fig 8, and the TEAM Workshop Problem 7, coil over the aluminum plate with asymmetrical hole, shown in Fig. 10.

Figs. 9 and 11 represent the scalar magnetic flux density distribution indicated with three semi-transparent isosurfaces. On the same figures, the outline of the analyzed model is also displayed. As can be seen, the regions which satisfy the user defined values of magnetic flux density can be identified with a glance of the display. The shape of isosurfaces indicates regions of the domain which have larger amount of magnetic flux density than that of the requested physical value. Additionally, as a result of semi-transparent display technique, it is possible to grasp not only the surface distributions but also the inside structure of each isosurface separately for a simultenous display of

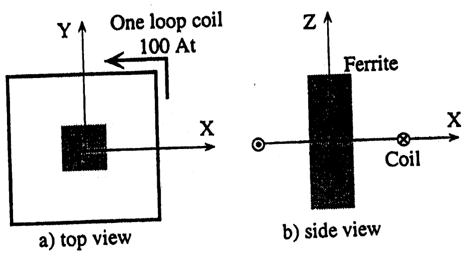

Fig. 8. A sample model.

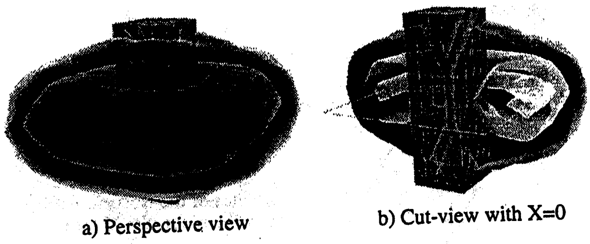

Fig. 9. Display of generated isosurface.

multiple isosurfaces. In both figures, we can also observe the cut-view display obtained by cross section of the generated isosurfaces with arbitrary three dimensional plane, which as shown here, is very beneficial for observation of complicated domains and distributions. Finally, Table I, shows some data and computation time for preprocessing (preparing data for extraction), extraction and display of three isosurfaces for both application models. We have to point out that the preprocessing time has to be executed only once during the data preparation period and later only the display time is needed for each isosurface display. From Table I, it is apparent that utilizing the proposed semitransparent visualization method one can interactively observe and analyze the desired scalar distribution in 3-D space.

IV. Conclusions

We proposed an isosurface visualization method as a new post-processing technique for displaying three dimensional scalar fields. Because the proposed algorithm exhibits high speed isosurface extraction and display, the visualization could be operated interactively with high precision and accuracy. Using the proposed visual system in comparison with the other traditional visualization techniques, it becomes possible to observe physical variable of importance using single or multiple isosurfaces utilizing semitransparent visualization. The proposed visualization technique could be advantageous for analysis and improvements of already developed electromagnetic devices, or as well for design and optimization of new ones.

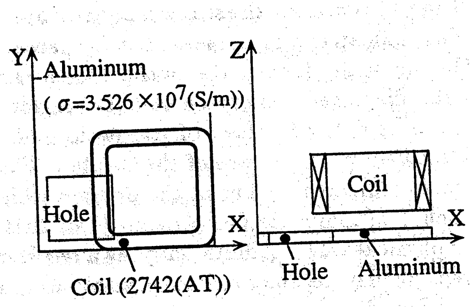

Fig. 10. Model of the TEAM Workshop Problem 7.

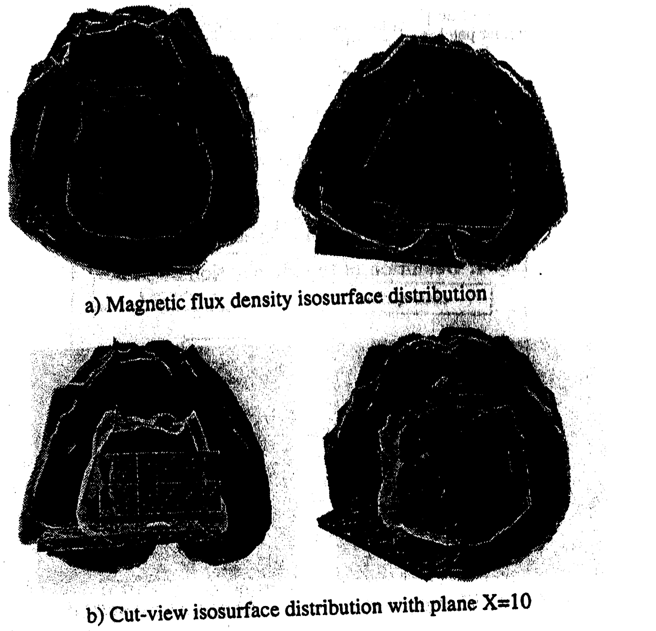

Fig. 11. Display of generated isosurface.

TABLE I
Computation time for isosurface extraction and display

Model	*Patches*	*Preprocessing time*	*Display time*
Fig. 8	3,472	0.11 (s)	0.33 (s)
Fig. 10	10,296	0.33 (s)	0.49 (s)

Pentium II 266MHz, RAM 96Mbyte

References

[1] H. Yamashita, T. Johkoh and E. Nakamae: "Interactive Visualization of Interaction between Magnetic Flux Density and Eddy Currents in a 3D Steady State Field", *IEEE Trans. on Magnetics*, Vol. 28, No. 2, pp.1778-1781, 1992.

[2] V. Čingoski, M. Ichinose, K. Kaneda and H. Yamashita: "Analytical calculation of magnetic flux lines in 3-D space," *IEEE Trans. on Magnetics*, Vol. 30, No. 5, pp.2912-2915, 1994.

[3] M. Oohigashi, V. Čingoski, K. Kaneda and H. Yamashita: "A New Method for 3-D Vector Field Visualization Utilizing Streamlines and Volume Rendering Techniques", *IEEE Trans. on Magnetics*, Vol. 34, No. 5, pp.3435-3438, 1998.

[4] W. Lorentson and H.Cline: "Marching Cubes: a High Resolution 3D Surface Construction Algorithm", *Computer Graphics*, Vol. 21, no. 4, July 1987.

[5] M. Bartsch, T.Weiland and M.Witting: "Generation of 3D Isosurfaces by Means of the Marching Cube Algorithm", *IEEE Trans. on Magnetics*, Vol. 32, No. 3, pp.1469-1472, 1996.