論 文
52B-6-1

전자소자의 3차원 형상최적화를 위한 구조변형 해석을 이용한 새로운 요소망 변형법

A Novel Mesh Regeneration Method Using the Structural Deformation Analysis for 3D Shape Optimization of Electromagnetic Device

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Abstract - A novel finite element mesh regeneration method is presented for 3D shape optimization of electromagnetic devices. The method has its theoretical basis in the structural deformation of an elastic body. When the shape of the electromagnetic devices changes during the optimization process, a proper 3D finite element mesh can be easily obtained using the method from the initial mesh. For real engineering problems, the method guarantees a smooth shape with proper mesh quality, and maintains the same mesh topology as the initial mesh. Application of the optimum design of an electromagnetic shielding plate shows the effectiveness of the presented method

Key Words : optimal shape design, design sensitivity analysis, structural deformation analysis, electromagnetic shield

1. Introduction

Optimal shape design is very important for improving the performance of electromagnetic devices. During the last decade, both deterministic and non-deterministic methods were developed and successfully applied to engineering design problems. The optimal shape design of electromagnetic devices repeats, as shown in Fig. 1, the processes of performance analysis, shape modification and mesh regeneration according to the optimization algorithm until a desired performance is obtained. For this reason, it is necessary to integrate a finite element mesh generator and optimization algorithm with a finite element performance analysis system to achieve a variety of designs automatically without regard to potential problems.

As for the finite element mesh regeneration, in two dimensional shape optimization problems, both the automatic mesh regeneration method and the mesh modification method are being used. In the former, the shape (boundary) of the device is first changed according to the optimization algorithm; the finite element mesh is then regenerated using the automatic mesh generator. In this method, the newly regenerated finite element mesh is definitely independent from the previous mesh, and the mesh topology may not be maintained, although a good mesh quality can be guaranteed. A preserved mesh topology is helpful for the successful application of efficient gradient methods [1]. On the other hand, with the latter method, the newly regenerated finite element mesh is dependent on the previous mesh and the same mesh topology is maintained as the previous mesh, but the mesh quality may be worse. In three dimensional shape optimization problems especially, the automatic mesh regeneration method is quite time consuming, and is very

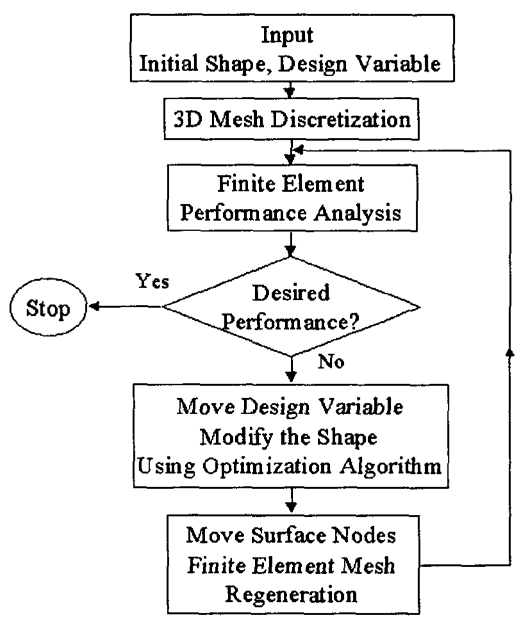

Fig. 1 General 3D shape optimization procedure

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接受日字 : 2002年 8月 29日
最終完了 : 2003年 5月 13日

difficult to combine with the finite element performance analysis and optimization programs. For this reason, the mesh modification method is preferred, especially in three dimensional shape optimizations.

The aforementioned research of the mesh modification methods in the optimal shape design can be classified into two types. In the first type, the directions of movement of each nodal point are specified according to the shape change, while the topology of the finite element connectivity is fixed as the initial one [2]. This method frequently fails to yield the optimum design by crashing elements or destroying convexity of finite elements if appropriate directions of the mesh movement are not specified by predicting the final shape in advance. In the second type, the interior nodes are generated automatically by using certain kinds of interpolation, e.g., line interpolation. This method may lead to severe mesh distortion. Another mesh modification method, introduced by Choi in the structural optimization, has its theoretical basis in the deformation theory of the elastic body under stress [3]. The structural consistency of the material guarantees smooth shape contours as the elastic body deforms. If the structural deformation of the shape is obtained by a finite element solution using a certain discretization, the deformation of the surface results in an evenly distorted mesh of the body. Therefore this mesh modification method can be used for the mesh regeneration of constant topology. Weeber used such idea in 2D shape optimization of electromagnetic devices [1].

In this paper, after the simple review of 3D stress analysis, a novel 3D finite element mesh relocation method for optimal shape design of electromagnetic devices is described. Some conclusions for its applications are also presented by the implementation of two test examples.

2. 3D Mesh Relocation Method Using Structural Deformation Analysis

The strain vector of an elastic body in three dimensional structural analysis is defined as follows [4]:

$$\varepsilon=\left[\frac{\partial u_x}{\partial x},\ \frac{\partial u_y}{\partial y},\ \frac{\partial u_z}{\partial z},\ \frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x},\ \frac{\partial u_y}{\partial z}+\frac{\partial u_z}{\partial y},\ \frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z}\right]^T \quad (1)$$

where the displacement vector is defined as follows:

$$\mathbf{u}=\begin{Bmatrix}u_x(x,y,z)\\u_y(x,y,z)\\u_z(x,y,z)\end{Bmatrix}=\sum_{i=1}^{4}\mathbf{N}_i\mathbf{a}_i^e=\left[\mathbf{I}N_i,\mathbf{I}N_j,\mathbf{I}N_m,\mathbf{I}N_p\right]\mathbf{a}^e \quad (2)$$

where $\mathbf{I}$ is the (3x3) identity matrix, $\mathbf{a}^e=\left[\mathbf{a}_i^e,\mathbf{a}_j^e,\mathbf{a}_m^e,\mathbf{a}_p^e\right]^T$, $\mathbf{a}_i^e=\left[u_{ix},u_{iy},u_{iz}\right]^T$, and the shape function N_i is defined as;

$$N_i=\left(a_i+b_ix+c_iy+d_iz\right)/6V \quad (3)$$

where V is the volume of the element, and the other symbols are defined as follows:

$$a_i=\det\begin{vmatrix}x_j & y_j & z_j\\x_m & y_m & z_m\\x_p & y_p & z_p\end{vmatrix},\quad b_i=-\det\begin{vmatrix}1 & y_j & z_j\\1 & y_m & z_m\\1 & y_p & z_p\end{vmatrix},$$

$$c_i=-\det\begin{vmatrix}x_j & 1 & z_j\\x_m & 1 & z_m\\x_p & 1 & z_p\end{vmatrix},\quad d_i=-\det\begin{vmatrix}x_j & y_j & 1\\x_m & y_m & 1\\x_p & y_p & 1\end{vmatrix}. \quad (4)$$

The relationship between the strain and stress for the linear elastic material is given as [4]:

$$\sigma=\mathbf{D}(\varepsilon-\varepsilon_0)+\sigma_0 \quad (5)$$

where σ_0 and ε_0 are the initial residual stress and initial strain, respectively, and σ is the stress consisting of direct and shear, ε is the corresponding strain, and $\mathbf{D}$ is the elasticity matrix given as follows:

$$D=\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\begin{bmatrix}1 & \frac{\nu}{(1-\nu)} & \frac{\nu}{(1-\nu)} & 0 & 0 & 0\\ & 1 & \frac{\nu}{(1-\nu)} & 0 & 0 & 0\\ & & 1 & 0 & 0 & 0\\ & & & \frac{(1-2\nu)}{2(1-\nu)} & 0 & 0\\ & & & & \frac{(1-2\nu)}{2(1-\nu)} & 0\\ symmetric & & & & & \frac{(1-2\nu)}{2(1-\nu)}\end{bmatrix} \quad (6)$$

where E is modulus and ν is Poisson's ratio.

Applying the finite element method with tetrahedral elements to (1) and (5), the matrix equation is obtained as follows:

$$[\mathbf{K}]\{\mathbf{a}\}=[\mathbf{f}] \quad (7)$$

where $\{\mathbf{a}\}=\{\mathbf{a}_1,\cdots,\mathbf{a}_N\}^T$ is the displacement of each node, [f]is the forcing load vector, and [K]is the stiffness matrix determined by the geometry and material constants of the elastic body as follows [4]:

$$\mathbf{K}_{ij}^{\ e} = \frac{E(1-\nu)}{36V_e(1+\nu)(1-2\nu)} \begin{bmatrix} K_{xxij} & K_{xyij} & K_{xzij} \\ K_{yxij} & K_{yyij} & K_{yzij} \\ K_{zxij} & K_{zyij} & K_{zzij} \end{bmatrix} \tag{8}$$

where:

$$K_{xxij} = b_i b_j + c_i c_j \frac{1-2\nu}{2(1-\nu)} + d_i d_j \frac{1-2\nu}{2(1-\nu)} \tag{8-1}$$

$$K_{yyij} = c_i c_j + b_i b_j \frac{1-2\nu}{2(1-\nu)} + d_i d_j \frac{1-2\nu}{2(1-\nu)} \tag{8-2}$$

$$K_{zzij} = d_i d_j + c_i c_j \frac{1-2\nu}{2(1-\nu)} + b_i b_j \frac{1-2\nu}{2(1-\nu)} \tag{8-3}$$

$$K_{xyij} = b_i c_j \frac{\nu}{(1-\nu)} + c_i b_j \frac{1-2\nu}{2(1-\nu)} \tag{8-4}$$

$$K_{xzij} = b_i d_j \frac{\nu}{(1-\nu)} + d_i b_j \frac{1-2\nu}{2(1-\nu)} \tag{8-5}$$

$$K_{yxij} = c_i b_j \frac{\nu}{(1-\nu)} + b_i c_j \frac{1-2\nu}{2(1-\nu)} \tag{8-6}$$

$$K_{yzij} = c_i d_j \frac{\nu}{(1-\nu)} + d_i c_j \frac{1-2\nu}{2(1-\nu)} \tag{8-7}$$

$$K_{zxij} = d_i b_j \frac{\nu}{(1-\nu)} + b_i d_j \frac{1-2\nu}{2(1-\nu)} \tag{8-8}$$

$$K_{zyij} = d_i c_j \frac{\nu}{(1-\nu)} + c_i d_j \frac{1-2\nu}{2(1-\nu)}. \tag{8-9}$$

Equation (7) is very similar to that of 3D static anisotropic magnetic analysis using nodal elements. The consistent and interrelated property of the deformations in an elastic body can be regarded as a design increment field. In this paper it is used for the mesh relocation during the optimal shape design of electromagnetic device by writing (7) as:

$$[\mathbf{K}]\{\Delta x\} = \{\mathbf{f}_x\} \tag{9}$$

where $[\mathbf{K}]$ is the global stiffness matrix for stress analysis, $\{\Delta x\}$ is the nodal displacement, and $\{\mathbf{f}_x\}$ is a fictitious load force to control the mesh density appropriately. The perturbation of the boundary can simply be considered as a displacement at the boundary. With no additional external forces and given displacements at the boundary, (9) can be used to find the displacements of all the nodes. Equation (9) can be rewritten as follows, in segmented form:

$$\begin{bmatrix} K_{bb} & K_{bd} \\ K_{db} & K_{dd} \end{bmatrix} \begin{Bmatrix} \Delta x_b \\ \Delta x_d \end{Bmatrix} = \begin{bmatrix} f_b \\ 0 \end{bmatrix} \tag{10}$$

where $\{\Delta x_b\}$ is the known perturbation of nodes on the boundary, $\{\Delta x_d\}$ is the unknown nodal displacement vector for the interior nodes, and $\{f_b\}$ is the fictitious boundary force acting on the boundary. The unknown interior nodal displacement vector can be obtained from the following equation:

$$[K_{dd}]\{\Delta x_d\} = -[K_{db}]\{\Delta x_b\} \tag{11}$$

In order to evaluate $\{\Delta x_d\}$, it is necessary to suppress all the degrees of freedom that represent the fixed shape contour of a domain in the finite element analysis. Since this structural analysis is merely used to get a proper relocation of the interior nodes from the displacement of the surface nodes, no emphasis is placed on simulating actual deformation of a physical structure. For this reason, the material parameters related to (8) could be chosen freely, and the boundary force in (10) is set to zero. In order to limit the computation efforts for mesh regeneration, only a part of the electromagnetic analysis region can be defined as the structural analysis. The overall flow chart is shown in Fig. 2.

If the nodal displacements are not substantial, the above mentioned method is sufficient to obtain a good mesh quality with a smooth shape. However, when the nodal

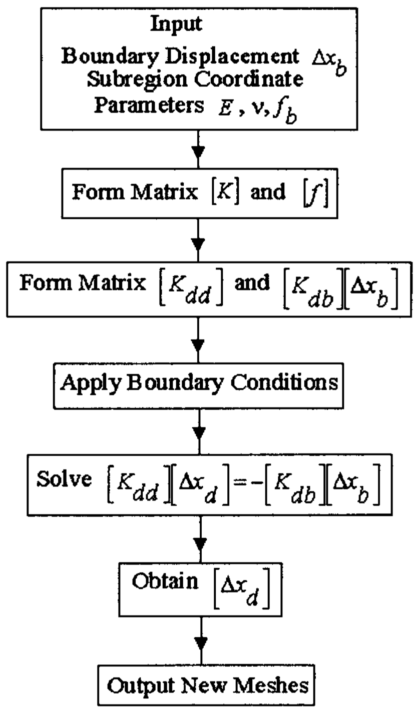


Fig. 2 Flow chart of 3D mesh regeneration method using structural stress analysis

displacements are quite large, some elements might be distorted. A mesh smooth scheme, in this case, to adapt interior nodes is suggested as follows [2]:

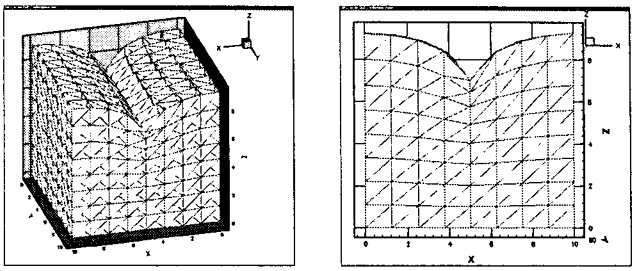
$$(\mathbf{x}_n)_{new} = (1-\alpha)(\mathbf{x}_n)_{old} + \alpha \sum_{i=1}^{n_{max}} \mathbf{x}_{ni} \Big/ n_{max} \tag{12}$$

where node n is relocated with a specified parameter α such that $0 < \alpha \leq 1$, n_{max} is the number of nodes connected to node n, and $\mathbf{x}_{ni}$ is the coordinate of node ni.

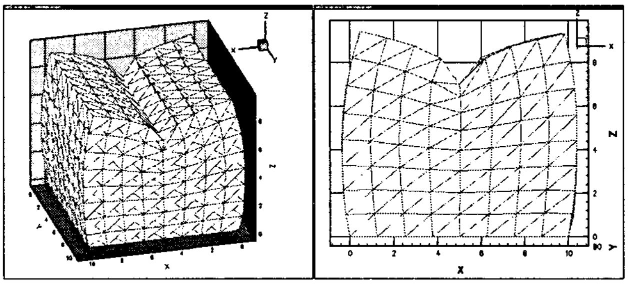
3. Numerical Applications

3.1 A block with deformed surface

In order to investigate the applicability of the proposed method to the 3D shape optimization, a simple block model is taken. During the application, the fictitious load force is set to zero, and E and ν are set to 0.5 and 0.3, respectively. When the nodal points in a line on the upper surface move, the regenerated meshes are compared, in Fig. 3, for different boundary conditions in the structural analysis. From the figure, where the nodal displacement of the moving node is 30% of the dimension of the model block, it can be seen that proper meshes with reasonable mesh quality are obtained with various boundary conditions. It can also be seen that when the finite element mesh is regenerated using the relocation method, the boundary surface remains smooth. However, when the nodal displacement is quite substantial (the displacement is 60% of the dimension of the block), as shown in Fig. 4, the regenerated meshes are distorted, and the mesh quality is not acceptable.

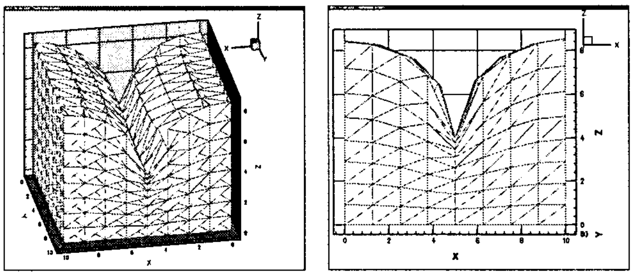


(a) when the upper surface is free to move while the four side surfaces are fixed.

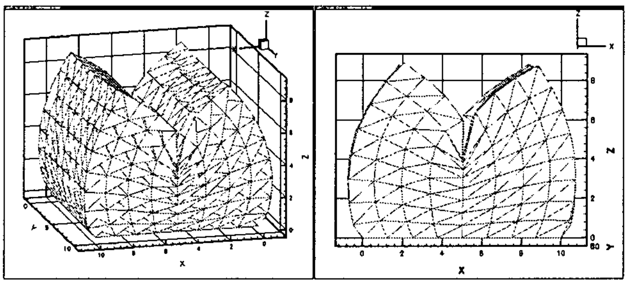


(b) when the upper and four side surfaces are free to move.

Fig. 3 The regenerated finite element meshes for different boundary conditions in structural analysis when the nodal displacement is small



(a) when the upper surface is free to move while the four side surfaces are fixed.



(b) when the upper and four side surfaces are free to move.

Fig. 4 The regenerated finite element meshes when the nodal displacement is quite large.

3.2 Optimal Design of an Electromagnetic Shield Plate

A 3D electromagnetic shielding model, shown in Fig.5, is taken and the shape of the shielding plate is optimized in order to keep the magnetic induction at the observing area to a minimum. The shielding plate is made of steel, of which electric conductivity and magnetic permeability are $\sigma = 7\times10^6$ $[(\Omega m)^{-1}]$ and $\mu_r = 800$, respectively, and the initial thickness is 10[mm]. The exciting current is 40000[AT] with power frequency. During the shape optimization procedure the thickness of the shielding plate is allowed to vary from 5[mm] to 30[mm].

The finite element analysis regions of electromagnetic fields and node relocation are compared in Fig. 6, and the boundary conditions for the structural analysis are given in Fig. 7, where x, y and z are the increments along x, y

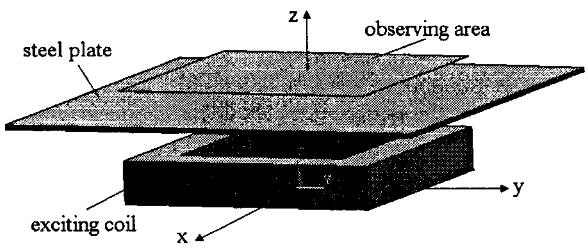


Fig. 5 The electromagnetic shield

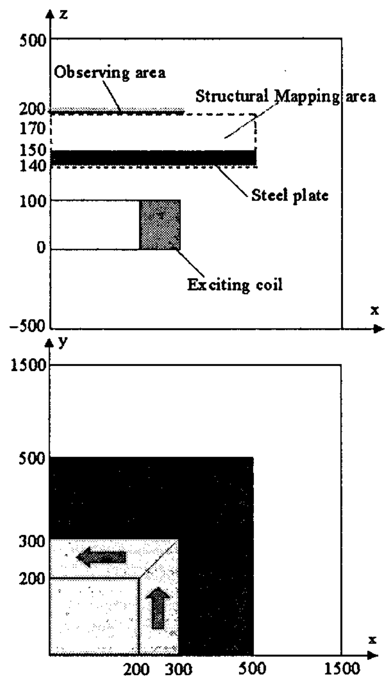


Fig. 6 The solving regions of electromagnetic and structural analysis

and z direction respectively. The objective function is defined as follows:

$$F(p)=\sum_{k=1}^{nb}\dot{\mathbf{B}}_k\cdot\dot{\mathbf{B}}_k^{*} \tag{13}$$

where nb is the number of observing points.

The design optimization is achieved by using the steepest descent method with the design sensitivity analysis, and the overall flow of the optimization is as follows:

Step 1: With the initial finite element meshes, perform the three-dimensional eddy current field analysis by solving

$$[\dot{S}][\dot{X}]=[\dot{Q}] \tag{14}$$

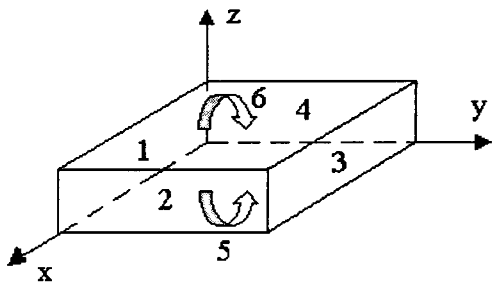


Fig. 7 The boundary conditions of the structural analysis model: $\Delta x_y=0$ at the surfaces 1 and 3, $\Delta x_x=0$ at the surfaces 2 and 4, $\Delta x_x=0$, $\Delta x_y=0$, $\Delta x_z=0$ at the surface 5.

where $[\dot{S}]$ and $[\dot{Q}]$ are the complex stiffness matrix and forcing vector, respectively, and $[\tilde{X}]$ is a complex state variable.

Step 2: Calculate the adjoint variable λ by solving:

$$[\dot{S}]^T\lambda=\frac{\partial F}{\partial \dot{X}} \tag{15}$$

Step 3: Calculate the design sensitivity of objective function F with respect to the design variable $[p]$:

$$\frac{dF}{d[p]^T}=\frac{\partial F}{\partial [p]^T}+2\mathrm{Re}\left\{\lambda^T\frac{\partial}{\partial [p]^T}\left[[\dot{Q}]-[S]\{\tilde{X}\}\right]\right\} \tag{16}$$

Step 4: Update the design variable:

$$[p]_{new}=[p]_{old}+\alpha\frac{dF}{d[p]^T}F_o/\left\|\frac{dF}{d[p]^T}\right\|^2 \tag{17}$$

where F_o is the objective function value and α is the relaxation factor.

Step 5: Generate a new finite element mesh by using the relocation method.

Step 6: Check the convergence, and go to Step 1.

The z coordinates of 91 nodes on the shielding plate surface are chosen as design variables to change the shielding plate shape. After thirteen iterations, the objective function became 51.16% of the initial value, as shown in Fig. 8. The optimized shape of the shielding plate is shown in Fig. 9.

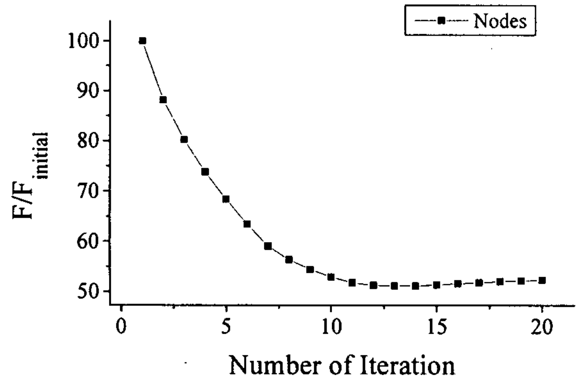


Fig. 8 Variation of the objective function value as iteration.

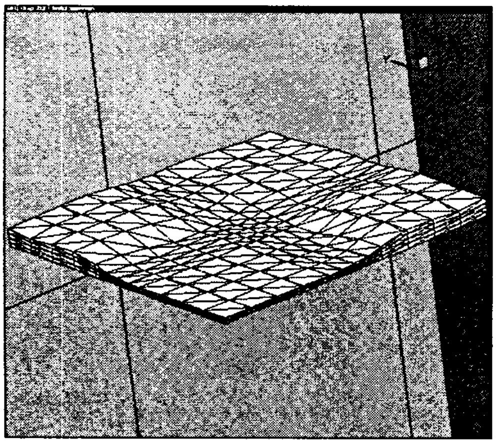


Fig. 9 The optimized shape of the shielding plate

4. Conclusions

A mesh regeneration method for 3D shape optimization is proposed. In this method, the displacements of the nodal points on the surface are mapped into the interior nodal points by using the deformation theory of the elastic body. The following conclusions are achieved from the numerical examples:

1) Because only a part of the electromagnetic field analysis can be taken for the structural analysis, the computational efforts are insignificant.
2) If the displacement of the design variable is not too large, the method gives a smooth contour with proper mesh quality.
3) Whether the geometric surface is parameterized or not, this method can be used to renew the finite element meshes.

Acknowledgements

This work was supported in part by Korea Research Foundation under Grant No. E00150

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