TYPHOON Code for 3-D Eddy Currents Simulation in Conducting Thin Shells

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Abstract

A 3-D code for numerical simulation of quasi stationary electromagnetic field of conducting shells was developed. An electrical potential vector was used for surface current calculation. The code gives a possibility to take into account of nonuniform surface resistance, holes in thin shells and symmetrically located regions. The results of conductive structures analysis are presented.

1 INTRODUCTION

Since the early 80-s interest in 3-D quasistatic field simulation has increased [1]. The problem is often to be solved for models of thin magnetic shells.

To define shell currents an approach using inductive coupled contours is applied [2]. It has also been known that surface current are conveniently described by current vector potential which must satisfy the condition $div\vec{J} = 0$. The solution can be obtained into the form of the expansion in eigenfunctions as is done in EDDYTORUS [3] and EDYCUFF [4] codes.

Formulation using integral-differential equations [5] is no less common and convenient for numerical realization. This approach allows to create a powerful algorithm considering nonuniformity of resistance ρ^*, holes in shells and symmetry properties of construction at rather limited number of unknown values of current potential in nodal points. The new TYPHOON code was developed to analyze the eddy currents in thin conducting shells. The areas of interest of this code are the same with the EDDYCUFF and EDDYTORUS codes.

2 3D FORMULATION USING THIN SHELLS MODEL.

It is assumed the thin conducting shell S with the thickness h is located in the space R^3. It is also assumed that conductivity σ is not the same through the whole volume of the conductors, but is the function of coordinates. The scalar function $P(\xi, \eta)$ may be used to define the surface electric current density $\vec{J}(\xi, \eta)$:

$$J_\xi = \frac{1}{h_\eta} \frac{\partial P}{\partial \eta} , \qquad J_\eta = -\frac{1}{h_\xi} \frac{\partial P}{\partial \xi} , \qquad (1)$$

where h_ξ, h_η — Lamet coefficients.

For uniform current density in the shell the equation

$$\mathrm{curl}\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

may be transformed

$$\frac{1}{h_\xi h_\eta} \left\{ \frac{\partial}{\partial \xi} \left(\rho^* \frac{h_\eta}{h_\xi} \frac{\partial P}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left(\rho^* \frac{h_\xi}{h_\eta} \frac{\partial P}{\partial \eta} \right) \right\} =$$

$$= \frac{\partial}{\partial t} (B_n^{(0)} + B_n^{(J)}) , \qquad (2)$$

where $\rho^* = \rho/h$, ρ — is a specific electrical resistance,

$B_n^{(0)}(t)$ — orthogonal to the surface S component of the external magnetic field (is known function of space coordinates and time),

$B_n^{(J)}(t)$ — is given by the formula:

$$B_n^{(J)}(\xi, \eta) = \frac{\mu_0}{4\pi} \int_{(S)} \frac{\left(\vec{J}(\xi', \eta') \times \vec{R}(\xi, \eta | \xi', \eta') \right)_n}{R(\xi, \eta | \xi', \eta')^3} dS \qquad (3)$$

(the points (ξ', η') and (ξ, η) are the point of source and the point of view, respectively).

According to (1) the curves $(P(\xi, \eta) = \mathrm{const})$ — are the lines of current $\vec{J}$ stream. It must be define

$$P = \mathrm{const}(\Gamma, \gamma_i)$$

on the outer contour Γ and holes contours γ_i of shell S.

The symmetry conditions of $\vec{J}$:

$$P = \mathrm{const}$$

are fulfilled on the boundaries of the calculation area crossing the plane symmetry.

The antisymmetry conditions of $\vec{J}$:

$$\frac{\partial P}{\partial n_{\mathrm{as}}} = 0$$

(n_{as} — is a normal of the antisymmetry counter, is a tangent of surface S) are fulfilled on the boundaries of the calculation area which are crossing the plane antisymmetry. One of the constants according to (1) may be equal zero, other constants are unknown.

The symmetry boundary conditions make it possible to solve equation (2) for reduced area, but the integrals (3) are to be defined over the whole region (including all shells).

At the moment $t = 0$ it is necessary to define the distribution $P(\xi, \eta)$. If $\vec{J}|_{t=0} = 0$ then $P(\xi, \eta)|_{t=0} = 0$.

This method may be used to analyze the strong and weak skin-effect.

Using a finite element method for solving the problem we get a system

$$M\frac{\partial \mathbf{P}}{\partial t} = (A_L + R)\mathbf{P} + \frac{\partial \mathbf{B}_n^{(0)}}{\partial t} \quad ,$$

where the matrixes M, A_L, R are the descretized form of (3).

We use the classical finite triangle elements for P on S.

The system of the differences equations is the system of a stiff nonlinear differential equations. We use the multi-layers C. W. Gear method [6]. For the equation:

$$\frac{\partial y}{\partial t} = f(y,t) \qquad y(0) = y_0,$$

where y and f are vectors the $(k+1)$-layer approximation is used:

$$\sum_{j=0}^{k} \alpha_j y_{n+j} = \tau \sum_{j=0}^{k} \beta_j f_{n+j}, \qquad \alpha_k = 1$$

where $y_n = y(t_n)$, $t_n = n\tau$, $f_n = f(y_n, t_n)$. The coefficients

$$\alpha_j, \quad \beta_j, \quad j = 1, 2, \ldots, 5$$

are known values [6].

3 NUMERICAL RESULTS.

Solutions for disk, rectangular plate and sphere for external electromagnetic field spasmodic increasing have been analyze to verify the code. Numerical results agree well with analytical solutions [9, 7, 8]. Some test and application problems were solved using TYPHOON for induced currents distribution in variable thin conducting shells. Fig. 1 shows eddy currents development in ring disk with 60^0 inset. The electrical resistance ρ_i^* of this inset is about 10 times that of the disk. Strong skin-effect eddy currents for different forms of holes in the rectangular plate with $\rho^* = const$ are presented in Fig. 2. TYPHOON code has been applied to investigate transient process for tokamak reactor conducting structures. Analysis for plasma envelopment conducting structures revealed that thin shells simulation provides a close approximation. As an example the calculation region for 1/16 part of TEXTOR [10] (in IPP KFA, Jeulich, Germany) vacuum vessel is shown in Fig. 3. 3-D eddy currents and mechanical forces were calculated during plasma current disruption. All essential constructive details were taken into account. Eddy currents distribution are shown in Fig. 4 at one time moment.

4 CONCLUSION

Developed TYPHOON code for calculation of eddy current in thin conducting shells is fairly efficient. It is completed with pre – and post – processors and available for rather non-expensive computational platforms. Thus, this code can be use to advantage as CAD/CAM element.
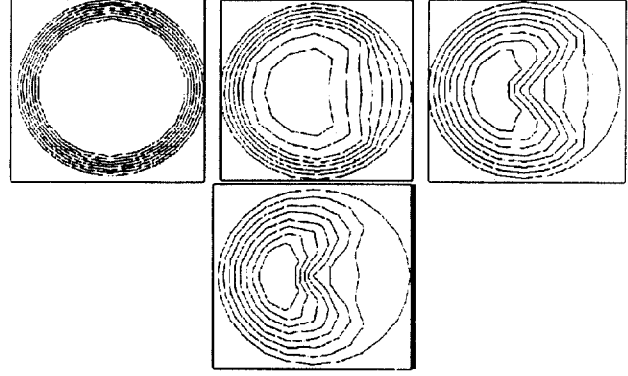

Figure 1: Eddy current development on disk with 60^0 inset: $\rho_i^* = 10\rho^*$, $t = 0, \frac{1}{30}\tau_0, 0.2\tau_0, \tau_0$.

5 ACKNOWLEDGMENTS

6 REFERENCES

[1] L. R. Turner. The TEAM Workshops: Their Relevance for Electromagnetics Computation in Nuclear Fusion. In Proc. "Electromagnetic Workshop and Meeting on the Industrial Applications of the Eddy Currents Codes." (Capri, 5–10 Oct. 1988). EUR 12 124 EN, 1989, pp. 95–104.

[2] D. W. Weissenburger and U. R. Christensen. MAG-18, 1982, p. 422–425.

[3] A. Kameari and Y. Suzuki. "Eddy Current Analysis by the Finite Element Circuit Method." In Proc. 7-th Symp. on Engineering Problem of Fusion Research (Knoxville, 1977). p. 1386–1392.

[4] A. Kameari and S. Niikuta. "EDDYTRAN Programm System for Eddy Current, Electromagnetic Force and Structural Analysis." In Proc. 10-th Symp. on Fusion Engineering (Philadelphia, 1983), p. 46–50.

[5] L. A. Tzeitlin Sov. J. Tech. Phys., vol. 14, 1970 p. 1305.

[6] C. W. Gear Comm. ACM, 1971, v. 14, p. 185

[7] A. Kameari. Transient Eddy Current Analysis on Thin Conductors with Arbitrary Connections and Shapes. J. of Computational Physics, v.42, p124-140, 1981.

[8] R. V. Thome, J. M. Tarrh. MHD and Fussion Magnets. John Willy and sons, NY, 1982.

[9] W. R. Smythe, Static and Dynamic Electricity, 3rd ed., McGraw-Hill, NY, 1968

[10] J. Ongena et al., Improved confinement at high density with an all silicon wall in TEXTOR Europhysics Conference. Abstracts 17c, pt. II p.127, 1993.
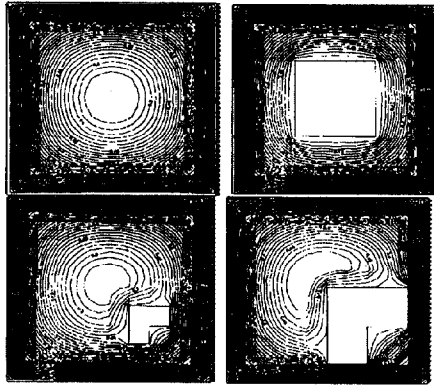
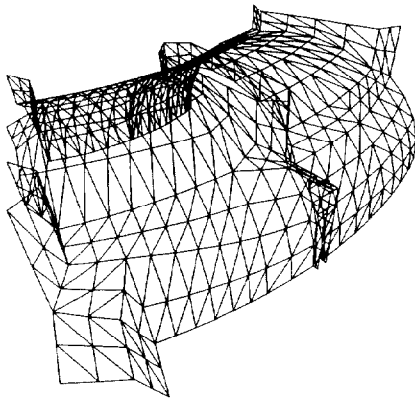Figure 2: Strong skin effect eddy currents on square plate ($\rho^* = $ const) with holes of different shapes.
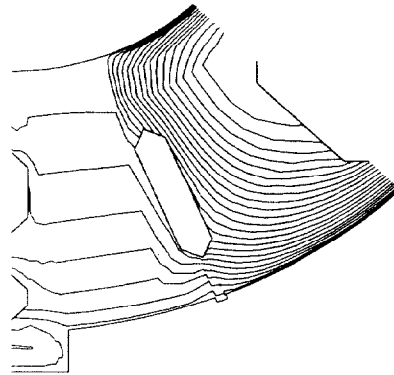

Figure 4: Eddy currents distribution ($t = 16$ ms).

Figure 3: The 1/16 part of TEXTOR vacuum vessel. Common view.