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

A.V. Belov, N.I. Doinikov, A.E. Duke, V.V. Kokotkov, V.P. Kukhtin, S.E. Sytchevsky
Efremov Scientific Research Institute of Electrophysical Apparatus, 189631, St-Petersburg, Russia

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 divJ = 0. The solution can be obtained into the form of the expansion in eigenfunctions as is done in EDDYTORUS [3] and EDCUFF [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 $\rho^*$, 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 $\mathbb{R}^3$. It is also assumed that conductivity $\sigma$ 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 $J(\xi, \eta)$:

$$J_\xi = \frac{1}{h_\eta} \frac{\partial P}{\partial \eta}, \quad J_\eta = -\frac{1}{h_\xi} \frac{\partial P}{\partial \xi},$$

where $h_\xi, h_\eta$ — Lamet coefficients.

For uniform current density in the shell the equation

$$\text{curl} \vec{E} = -\frac{1}{h} \frac{\partial \vec{B}}{\partial t}$$

may be transformed

$$\frac{1}{h_\xi h_\eta} \left\{ \frac{\partial}{\partial \xi} \left( \rho^* \frac{h_\eta}{h_\xi} \frac{\partial P}{\partial \xi} \right) + \frac{\partial}{\partial \eta} \left( \rho^* \frac{h_\xi}{h_\eta} \frac{\partial P}{\partial \eta} \right) \right\} = \frac{\partial}{\partial t} (B_n^{(0)} + B_n^{(J)}), \quad (2)$$

where $\rho^* = \rho/h$, $\rho$ — 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:

$$B_n^{(J)}(\xi, \eta) = \frac{\mu_0}{4\pi} \int_{(S)} \frac{(\vec{J}(\xi, \eta) \times \vec{R}(\xi, \eta) \times \vec{a})}{R(\xi, \eta) \times \vec{a}^3} \cdot dS \quad (3)$$

(the points $\xi$, $\eta$ and $(\xi, \eta)$ are the point of source and the point of view, respectively).

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

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

on the outer contour $\Gamma$ and holes contours $\gamma_i$ of shell $S$. The symmetry conditions of $\vec{J}$:

$$P = \text{const}$$

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

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

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

($n_{\text{as}}$ — 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 $J_\eta|_{t=0} = 0$ 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

$$M \frac{\partial P}{\partial t} = (A_L + R)P + \frac{\partial B_n^{(0)}}{\partial t},$$

where the matrices $M$, $A_L$, $R$ are the discretized 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 multilayers C. W. Gear method [6]. For the equation:

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

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

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

where $y_n = y(t_n), \quad t_n = n\tau, \quad f_n = f(y_n, t_n)$. 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 current development in ring disk with $60^\circ$ inset. The electrical resistance $\rho_n$ 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 $\rho' = \text{const}$ 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.

5 ACKNOWLEDGMENTS

The author are thankful Dipl.-Ing. B. Giesen and Dipl.-Ing. F. H. Bohn for support and fruitful discussions, Dr. O. G. Filatov and Dr. Yu. P. Severgin for careful attitude and support.

6 REFERENCES

Figure 2: Strong skin effect eddy currents on square plate ($\rho^* = \text{const}$) with holes of different shapes.

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

Figure 4: Eddy currents distribution ($t = 16 \text{ ms}$).