§41. Reconstruction of 3-D Magnetic Field Profile Outside Plasma in Large Helical Device

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1. Introduction

An approach has been proposed to reconstruct the 3-D magnetic field profile outside the plasma in the Large Helical Device (LHD) using magnetic sensor signals. The method is an extension of the Cauchy condition surface (CCS) method [1] to a 3-D space.

2. Three-dimensional CCS method

The 3-D CCS is assumed to have a torus shape and to be located in the plasma region. The Dirichlet and the Neumann conditions along the CCS are now the vector potential and its derivative, respectively. The first step of the analysis is to obtain both types of boundary conditions on the CCS in such a way that they will be consistent with the magnetic sensor signals.

2.1 Vector Laplacian

One here adopts the Cartesian coordinate system for the analysis so that the vector Laplacian has the simple relationship

$$(\nabla^2 \boldsymbol{A})_k = \nabla^2 A_k \quad (k = x,\, y,\, z)\,. \tag{1}$$

2.2 Hypothetical assumption of vacuum field

One assumes that there is no plasma current, i.e., vacuum everywhere outside the CCS. The effect of the actual plasma current is transformed into the hypothetical CCS.

2.3 Sensor signals described using vector potential

The field sensor signals are assumed to be given in terms of B_r, B_φ and B_z. They are described using A_x, A_y and A_z, as

$$B_R = \sin\varphi \frac{\partial}{\partial z} A_x - \cos\varphi \frac{\partial}{\partial z} A_y + \left(-\sin\varphi \frac{\partial}{\partial x} + \cos\varphi \frac{\partial}{\partial y} \right) A_z, \tag{2a}$$

$$B_\varphi = \cos\varphi \frac{\partial}{\partial z} A_x + \sin\varphi \frac{\partial}{\partial z} A_y + \left(-\cos\varphi \frac{\partial}{\partial x} - \sin\varphi \frac{\partial}{\partial y} \right) A_z \tag{2b}$$

and

$$B_Z = -\frac{\partial}{\partial y} A_x + \frac{\partial}{\partial x} A_y\,. \tag{2c}$$

The magnetic flux loop signal is defined as the circular integral of vector potential along a closed line, i.e.,

$$\psi = r\int_0^{2\pi} \left\{ -A_x(\varphi)\sin\varphi + A_y(\varphi)\cos\varphi \right\} d\varphi\,. \tag{3}$$

2.4 Boundary integral equations

One derives boundary integral equations (BIEs) in terms of A_x, A_y and A_z for field sensors and flux loops, following Eqs.(2a), (2b), (2c) and (3). Further, one should add BIEs for points along the CCS. The set of these BIEs are solved simultaneously. In the BIE for a flux loop, the portions related to the fundamental solution are integrated along the flux loop.

Once all the values of A_k and $\partial A_k / \partial n$ $(k = x, y, z)$ along the CCS have been given, the magnetic field can be calculated for arbitrary points.

2.5 Rotational Symmetry of Vector Potential

The rotational symmetry of the plasma is incorporated into the formulation to reduce the number of unknowns. This is based on the "linear transformation" using the rotation angle $\Delta\varphi^{(k)}$ from $\mathbf{A}^{(1)}$ to $\mathbf{A}^{(k)}$ in Cartesian coordinates:

$$\begin{pmatrix} A_x^{(k)} \\ A_y^{(k)} \\ A_z^{(k)} \end{pmatrix} = \begin{pmatrix} \cos\Delta\varphi^{(k)} & -\sin\Delta\varphi^{(k)} & 0 \\ \sin\Delta\varphi^{(k)} & \cos\Delta\varphi^{(k)} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} A_x^{(1)} \\ A_y^{(1)} \\ A_z^{(1)} \end{pmatrix}. \tag{4}$$

3. Numerical examples

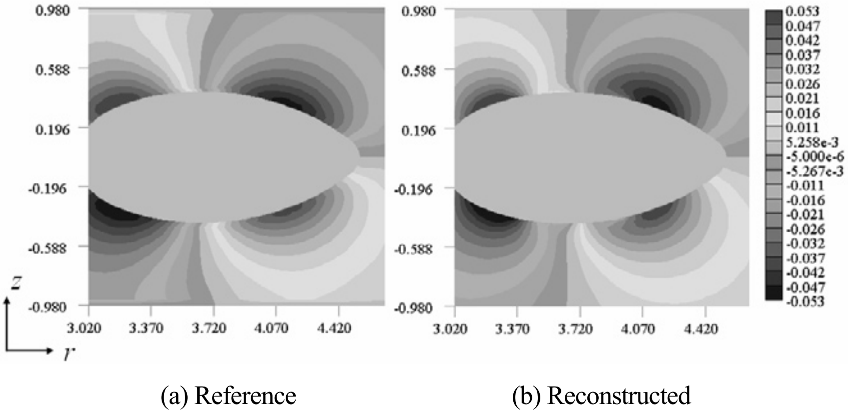
One assumes 20 flux loops and 451 field sensors outside the plasma. The cross section of the CCS tube is a circle having a radius of 0.075m, which centre is set to be r=3.7m and z=0.0m. Considering the 1/5 rotational symmetry, the CCS is divided into 32 boundary elements, each of which has 9 nodal points.

The reconstructed field outside the outermost magnetic surface (OMS) agrees well with the reference field that had been given beforehand using the HINT code [2]. Figure 1 shows an example for the r-component of the field. As the magnetic fields computed using the CCS method have no physical meaning inside the OMS, they are not drawn in Fig.1.

4. Conclusion and further remarks

A 3-D CCS method code has been developed for 3-D plasma in the LHD. The magnetic field outside the OMS has been well reconstructed. One needs to seek a practical way of drawing the OMS through the reconstructed field.

[1] Kurihara, K., *Fusion Eng. Des.*, **51-52** (2000) 1049.
[2] Harafuji, K. et al., *J. Comput. Phys.,* **81** (1989) 169.



(a) Reference (b) Reconstructed

Fig.1 Contours of B_r and the outermost magnetic surface